Precipitation Characteristics Affecting Hydrologic Response of Southwestern Rangelands

U.S. Department of Agriculture
Agricultural Research Service
Agricultural Reviews and Manuals•ARM-W-34/January 1983

A copy of this publication is available upon request from the Southwest Rangeland Watershed Research Center, Tucson, Ariz. 85705.

International Standard Serial Number (ISSN) 0193-3760

Agricultural Research Service, Agricultural Reviews and Manuals, Western Series, No. 34, January 1983

Published by Agricultural Research Service (Western Region), U.S. Department of Agriculture, Oakland, Calif. 94612

ABSTRACT

This publication provides the most up-to-date and definitive source of precipitation data for ranchers and others involved in range management and range renovation programs. The period of record (25 years) is such that specific probabilities now can be assigned to rainfall occurrences on an areal basis to provide a good estimate of the chance of success or failure of any range management or renovation program as well as expected amounts of rainfall in a given basin for downstream water users.

KEYWORDS: Hydrologic cycle, precipitation effectiveness, rangeland management, rangeland watersheds, range renovation.

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PRECIPITATION CHARACTERISTICS AFFECTING HYDROLOGIC RESPONSE OF SOUTHWESTERN RANGELANDS

Herbert B. Osborn[1]

INTRODUCTION

Rangelands comprise about 40 percent of the earth's land area, and about 80 percent of rangeland is classified as either arid or semiarid. Most rangelands in the southwestern United States are arid or semiarid. Rangelands provide forage for livestock and are generally under climatic stress. Grazing increases this stress, which in turn may reduce forage, increase erosion, and encourage flood potential and the proliferation of nonbeneficial plant species.

The U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), has been involved in rangeland research since 1953 (*4*).[2] In the Southwest, the ARS has continued research initiated in 1939 by the Soil Conservation Service (SCS) near Safford, Ariz., and west of Albuquerque, N. Mex. (fig. 1). In 1954, experimental rangeland watersheds were established at Tombstone, Ariz., and Santa Rosa, N. Mex. (fig. 1). The USDA Southwest Rangeland Watershed Research Center (SWRWRC) was established in 1961 to conduct rangeland research on water in the Southwest. The principal experimental areas were the Walnut Gulch and Alamogordo Creek experimental rangeland watersheds. Cooperative efforts were also initiated in 1966 at Ft. Stanton, with New Mexico State University, and in 1975, near Tucson, with the U.S. Forest Service (Santa Rita Experimental Range), but most analyses have been based on data collected from Walnut Gulch and Alamogordo Creek.

The mission of the SWRWRC is to study the hydrologic characteristics of rangeland watersheds and the effects of changing land use and practices on the hydrologic cycle. This includes rainfall characteristics, surface and subsurface water quality and quantity, erosion, sediment movement and deposition, and the present and potential use of available water. The dense raingage networks serve two purposes: to measure precipitation as input to a complex hydrologic system (watershed) and to provide data essential for developing precipitation models for ungaged watersheds.

In the past 20 years, SWRWRC staff published 51 technical papers wholly or partially concerning precipitation in Arizona and the Southwest. Since runoff-

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[2]Italic numbers in parentheses refer to Literature Cited, p. 23.

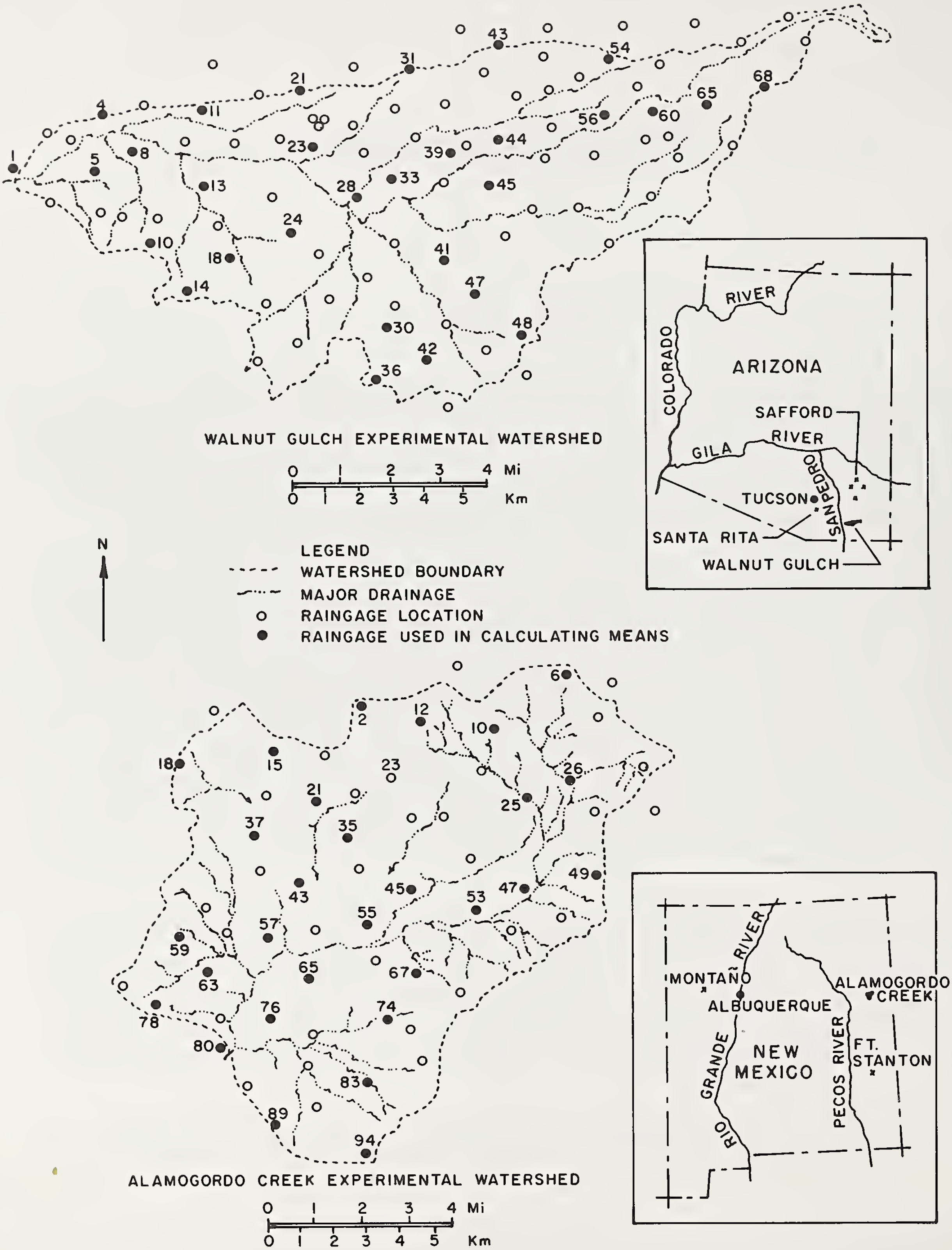

Figure 1.--Location of USDA experimental watersheds and major precipitation networks in Arizona and New Mexico.

producing rainfall has been of primary interest at the SWRWRC, summer convective storm rainfall has been most thoroughly studied, and only a few publications have included winter precipitation. In this publication, the results of 25 years of research, primarily from records from the dense raingage networks in Arizona and New Mexico, are reported and correlated. Rainfall amounts, intensities, durations, areal extents, movement, character, and frequencies are analyzed. Several analyses described in earlier papers are repeated, and now that more data are available, several new analyses are presented. Most of the bibliography is from SWRWRC publications, but other pertinent publications are included for continuity in reporting rangeland research in the southwestern United States.

EXPERIMENTAL WATERSHEDS

Walnut Gulch

The 150-km^2 (58-mi^2) Walnut Gulch experimental rangeland watershed lies in the San Pedro Valley of southeastern Arizona (fig. 1). Desert shrubs dominate the lower two-thirds of the watershed and desert grasses the upper one-third. The watershed is taken to be representative of semiarid rangelands in southeastern Arizona, southwestern New Mexico, and northern Sonora, Mexico. A raingage network was established in 1954 and 1955, with 40 24-hr weighing-type recording raingages in continuous operation since 1956 (*44*). Recording gages were added within and adjacent to the watershed during the early years of the study, and the current network consists of 95 weighing-type recording raingages representing an area of about 175-km^2 (68-mi^2). Radar was installed in the early 1960's to aid in quantifying rainfall, but it did not prove helpful. More recent studies, however, have suggested that radar might be helpful in understanding the systems that produce intense rainfall (*39*).

Alamogordo Creek

The 174 km^2 (67-mi^2) Alamogordo Creek experimental rangeland watershed is about 55 km (35 mi) east of Santa Rosa and is typical of rangeland on the western edge of the Llano Estacado (Staked Plain) (fig. 1). The watershed consists primarily of a flat, recessed basin almost entirely surrounded by a steep escarpment and is predominantly grassland with scattered intrusions of brush. As part of the watershed research program, a network of raingages was established in 1955, with 57 24-hr weighing-type recording raingages in continuous operation from 1956 through 1978. Most of the raingages were located on the floor of the watershed basin, but a few were scattered along the rim. There is a difference of 100 to 200 m between the elevation of the basin floor and the surrounding plateau.

Safford and Montano Grant Watersheds

The four small rangeland watersheds of about 250 ha (1-mi^2) each, located in the vicinity of Safford, were dispersed in an elliptical area of about 400-km^2

(150-mi^2) (fig. 1). The watersheds are mixed brush- and grass-covered, with brush predominating in several areas. The watersheds vary from arid at the lowest elevation, near the Gila River, to semiarid at the highest elevation above Safford, with more abundant vegetation on the higher watersheds. Precipitation was recorded by two 12-hr weighing-type recording raingages on each watershed. In contrast, the three very small (less than 40 ha) Montana Grant watersheds were located within a 250-ha (1-m^2) area west of Albuquerque and the Rio Grande. The watersheds are mostly brush covered, with some sparse grassland. Precipitation was recorded with five 12-hr weighing-type recording raingages. Precipitation records from these two watersheds furnished uninterrupted precipitation data from 1939 through 1976, when precipitation and runoff measurements were discontinued.

Ft. Stanton

Two very small (less than 10 ha) paired mountain rangeland watersheds, one grazed and one ungrazed, near Ft. Stanton were instrumented in a cooperative effort with New Mexico State University in 1966 (fig. 1). Both watersheds are predominantly grass covered. Precipitation is measured by two 12-hr weighing-type recording raingages.

Santa Rita Experimental Range

In 1975, a cooperative effort was initiated with the U.S. Forest Service on the Santa Rita Experimental Range, about 80 km south of Tucson (fig. 1). Eight very small (less than 5 ha) rangeland watersheds were instrumented with seven 6-hr and three 7-day weighing-type recording raingages. The watersheds are mixed grass and brush covered, and grazing is controlled. The watersheds are representative of rangelands on the alluvial fans at the base of mountain ranges in southern Arizona.

CLIMATE

The range of elevations (40 to 4200 m) in Arizona assures a wide range of climatic conditions (*49*). Much of the State receives less than 250 mm average annual rainfall; temperatures exceeding 120°F are recorded in the dry southwestern part of the State. The region of highest rainfall and corresponding moderate temperatures crosses the State from the southeast to the northwest (*49*). The SWRWRC experimental watersheds are in the valleys of southeastern Arizona, where annual rainfall is 250 to 350 mm (*4*, *13*, *14*, *18*, *19*, *22*, *44*). New México climate also varies in temperature and precipitation, and annual precipitation at the SWRWRC experimental rangeland watersheds is also 250 to 350 mm (*1*, *13*, *14*, *19*, *44*, *45*, *52*, *55*). In the Southwest, precipitation is bimodal, with slow-moving cold fronts supplying the lift for most winter precipitation and convective lifting of moist southerly airmasses producing most of the summer rainfall.

In 1960, Sellers (*49*) reported that the moisture for July and August convective storms in Arizona came entirely from the Gulf of Mexico. This theory was accepted until early in the 1970's (*17*, *18*, *19*, *22*, *34*, *35*, *37*, *45*). Furthermore, Sellers (*49*) reported that, "every four or five summers, when conditions are right, a tropical storm may come rampaging through Arizona" from the southwest (Pacific Ocean). In 1973, Hales (*7*) suggested that "surges of moisture" from the Pacific Ocean into Arizona were far more common than previously thought and were a significant source of moisture for convective storms. He felt that, in the past (before weather satellites), only the larger events had been recognized as originating in the Pacific Ocean. Both the Pacific Ocean and Gulf of Mexico are now recognized as significant sources of moisture for summer convective storms in the Southwest, with Gulf of Mexico moisture more prevalent in New Mexico and Pacific Ocean moisture more common in Arizona (*21*, *36*, *38*).

Winter rains and snow are generally low-intensity events associated with slow-moving cold fronts, although occasionally, surges of moist air can push into Arizona in the winter and produce convective storms.

Until the USDA established dense raingage networks on Walnut Gulch and Alamogordo Creek, the role of summer convective rainfall in the Southwest was uncertain. For example, Sellers (*49*) reported that "contrary to popular notion, rainfall intensities in Arizona are not excessive," and "summer rains are only slighty more intense than winter rains." His conclusions were based on hourly records from scattered recording raingages and daily rainfall from standard gages. Relatively few recording raingages are scattered across Arizona and New Mexico (*19*). Records from Walnut Gulch and Alamogordo Creek raingage networks have shown that convective storms can produce high intensities for short durations and small areal extents, but these high intensities are rarely recorded, because of the sparse raingage sampling network in Arizona and New Mexico (*9*, *19*, *23*, *27*, *28*, *37*, *40*, *42*, *45*). Records from Walnut Gulch and Alamogordo Creek also show that over 95 percent of surface runoff results from summer convective rainfall (*1*, *22*, *34*, *35*, *43*, *44*).

ANNUAL AND SEASONAL PRECIPITATION

There are both similarities and significant differences in annual and seasonal precipitation on Walnut Gulch and Alamogordo Creek. Most earlier reports from the SWRWRC concentrated on data from one or the other of the watersheds, with Walnut Gulch being cited most often. Early reports, based on 30 gages and 11 years of record on Walnut Gulch, showed about 70 percent of the annual precipitation of 285 mm occurred from May through September, with 55 percent occurring in July and August (*22*). Summer rainfall exceeded winter precipitation in all of the first 11 years of record on Walnut Gulch. Only 5 percent of the annual precipitation was recorded in April, May, and June, with May by far the driest month (*18*). Based on 10 years of record, from 30 gages on Alamogordo Creek, summer rainfall (May-September) produced about 80 percent of the annual precipitation of 284 mm, with the driest months being in the winter (*1*). Over 50 percent of the annual precipitation occurred in June, July, and August (*1*).

Later reports, based on records from 30 gages and 25 and 23 years of record, respectively, on Walnut Gulch and Alamogordo Creek, placed more confidence in mean values for annual and seasonal precipitation (tables 1 and 2). On Walnut Gulch, annual precipitation was 288 mm; summer rainfall (May-September) was 193 mm (67 percent of annual); and winter precipitation was 95 mm. July-August rainfall was 148 mm or 52 percent of the annual precipitation. Summer rainfall exceeded winter precipitation in 22 of the 25 years on Walnut Gulch. On Alamogordo Creek, annual precipitation was 315 mm; summer rainfall (May-September) was 233 mm (75 percent of annual); and winter precipitation was 82 mm. With the longer period of record, the mean annual and summer precipitation at Alamogordo Creek are significantly higher and the mean winter precipitation is significantly lower than at Walnut Gulch. There is significant difference between the two watersheds in April, May, and June rainfall (fig. 2).[3] Mean monthly rainfall increases progressively on Alamogordo Creek during April, May, and June (78 mm for the 3 months), whereas on Walnut Gulch, these are the driest months of the year (15 mm).

Fletcher (5), using several long-term U.S. Weather Bureau Stations in Arizona and New Mexico, investigated precipitation effectiveness (PE) based on the Thornthwaite (*54*) equation:

$$PE = \sum_{1}^{12} 115 \left[\frac{P}{T-10}\right]^{10/9} = \sum_{1}^{12} (pr)$$

where P = mean precipitation for each month (inches);
T = mean temperature for each month (°F) ($T > 10$); and
pr = precipitation effectiveness ratio for each month.
The Thornthwaite equation, converted to SI units and degrees Celsius (°C), is:

$$PE = \sum_{1}^{12} 3.28 \left[\frac{P}{T^{9/5} + 22}\right]^{10/9} = \sum_{1}^{12} (pr)$$

Thornthwaite's equation with 25 and 23 years of precipitation records emphasizes the differences in PE between Walnut Gulch and Alamogordo Creek (tables 1 and 2, fig. 3). On Alamogordo Creek, a plot of "pr" by months shows the steady increases in PE during April, May, and June (4.0 sum), assuring a relatively long and effective growing season. On the other hand, "pr" is near zero (0.6) in April, May, and June on Walnut Gulch, when precipitation is very low and temperatures very high. The difference in PE for April, May, and June of 3.4 is essentially the difference in annual PE between the two watersheds. Range management programs on Walnut Gulch must rely on the "surges" of moist air in July and August, whereas management should be more flexible on Alamogordo Creek because of the longer effective growing season. Finally, on Walnut Gulch a significant PE during the winter, 4.7 from December through March, allows the deep-rooted plants, such as brush, to benefit from winter moisture and have an advantage over grasses during the dry, warm spring months.

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[3]Figures 2 to 44 follow the Literature Cited, beginning on p. 30.

Table 1.--*Mean monthly precipitation (mm), temperature (°C), and monthly precipitation effectiveness (Pr) for Walnut Gulch (30 raingages; 25 yr of record)*

Walnut Gulch	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Summer	Winter	Annual
Precipitation.	17	12	14	4	3	8	80	68	34	20	10	18	193	95	288
Temperature	8	9	12	16	20	24	27	25	23	18	13	9	--	--	--
Pr	1.4	0.9	0.9	0.2	0.1	0.3	3.8	3.3	1.7	1.1	0.6	1.5	9.2	6.6	15.8

Table 2.--*Mean monthly precipitation (mm), temperature (°C), and precipitation effectiveness (Pr) for Alamogordo Creek (30 raingages; 25 yr of record)*

Alamogordo Creek	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Summer	Winter	Annual
Precipitation.	6	8	10	13	25	40	76	60	32	26	10	9	233	82	315
Temperature	4	6	8	14	19	24	26	25	21	16	9	5	--	--	--
Pr	0.6	0.7	0.8	0.8	1.3	1.9	3.6	2.9	1.6	1.6	0.8	0.8	11.3	6.1	17.4

Variability in Time

Precipitation varies considerably from season to season from year to year on both Walnut Gulch and Alamogordo Creek. For Walnut Gulch (1956-80), annual precipitation varied from 170 mm in 1956 to 378 mm in 1977 (fig. 4); summer rainfall varied from 104 mm in 1960 to 290 mm in 1966 (fig. 6); and winter precipitation varied from 25 mm in 1966-67 to 233 mm in 1978-79 (fig. 8). For Alamogordo Creek (1956-78), annual precipitation varied from 142 mm in 1956 to 564 mm in 1960 (fig. 5); summer rainfall varied from 102 mm in 1956 to 400 mm in 1960 (fig. 7); and winter precipitation varied from 13 mm in 1966-67 to 177 mm in 1972-73 (fig. 8). Summer rainfall was more variable from year to year on Alamogordo Creek, whereas winter precipitation was more variable on Walnut Gulch. There were no significant positive or negative correlations between either seasons or years on either watershed or for annual or seasonal precipitation between watersheds.

Variability in Space

Because of spatial variability of convective rainfall, analyses of data in the mid-1960's showed significant variability in point monthly precipitation on both Walnut Gulch and Alamogordo Creek for both winter and summer periods (*1*, *22*). It was expected that most of this variability would disappear with a longer record or could be explained by differences in elevation. This was true with the winter months, but there was considerable unexplained point variability for summer monthly point rainfall on both watersheds. The range in the ratios of maximum and minimum mean monthly point rainfall for Walnut Gulch varied from 0.88 to 1.10, 0.88 to 1.10, and 0.80 to 1.34 for July, August, and September, respectively. For Alamogordo Creek, the range for July and August was 0.88 to 1.14 and 0.89 to 1.17, respectively. The differences were generally greater than ±10 percent for the summer months, and greater than ±20 percent for the winter.

There are large differences in yearly summer and annual point precipitation measurements on both Walnut Gulch and Alamogordo Creek (figs. 4-8). The location of maximum and minimum point summer and annual precipitation amounts in any given year appears to be random and is not explained by elevation or aspect. The maximum amounts were commonly more than twice the minimums, and the differences in mean point values were still apparent with 25 and 23 years of record on Walnut Gulch and Alamogordo Creek, respectively (figs. 9-14). On Walnut Gulch, RG 1, which is at the lowest elevation, is well below the mean seasonal and annual precipitation for the watershed; however, the records from other gages on the watershed do not indicate an elevation-related pattern. On Alamogordo Creek, there is a correlation between annual and seasonal precipitation and elevation. Most of the lowest seasonal and annual amounts have been recorded on the lower elevations of the watershed, and all of the greater amounts have been recorded at higher elevations.

Correlations of mean annual and seasonal precipitation with elevation illustrate the similarities and differences between the two watersheds (figs. 15 and 16). There is only a slight positive slope to correlations for Walnut Gulch

--0.073 for annual, 0.047 for summer, and 0.027 for winter. The r^2 values are 0.21, 0.19, and 0.16 for annual, summer, and winter correlations, respectively, indicating that there is no statistical improvement in using the best fit rather than the mean as an indicator for any of the three plots and that there is still considerable variability in mean precipitation that is not explained by elevation. On Alamogordo Creek, there is a correlation between elevation and summer rainfall and a weaker, but apparent, correlation between elevation and winter precipitation. Annual precipitation, which is highly correlated to summer rainfall, is also correlated with elevation. Positive slopes are 0.15, 0.11, and 0.04, respectively, for annual, summer, and winter precipitation versus elevation. R^2 values, however, are only 0.51, 0.45, and 0.36, which indicates that there is either an unexplained variability, or that the random storm distribution was not completely smoothed in 23 years of record.

The apparently random patterns of yearly summer rainfall are illustrated with isohyetal rainfall maps for selected summer seasons of 1967, 1969, and 1977 for Walnut Gulch and 1964, 1969, and 1972 for Alamogordo Creek (figs. 17-22). The minimum and maximum point rainfall amounts for Walnut Gulch for the 1967 summer season were 141 mm and 325 mm (fig. 17), with the maximum 2.3 times the minimum. In 1969, the minimum and maximum were 130 mm and 368 mm, with the maximum 2.8 times the minimum (fig. 18). Furthermore, the lower end of the watershed received well above average summer rainfall. In 1977, a relatively dry summer, the minimum and maximum values of 169 mm and 291 mm were both recorded on the upper end of the watershed (fig. 19), and the maximum was 1.72 times the minimum. For 25 yr of record, the ratio of average maximum to minimum point summer rainfall was 2.1, with a range of 1.5 to 2.8.

For Alamogordo Creek, the minimum and maximum summer rainfall depths in 1972 were 307 mm and 547 mm, with the maximum 1.8 times the minimum, and both maximum and minimum were recorded at valley stations (fig. 20). In 1969, the minimum and maximum point depths were 270 mm and 549 mm, with the maximum 2.0 times the minimum (fig. 21). In 1964, a relatively dry year, the minimum and maximum were 72 and 141, with the maximum about 2.0 times the minimum, and the maximum was recorded at a higher elevation (fig. 22). The ratio of average maximum to minimum summer point rainfall was 1.9, with a range of 1.4 to 2.6. Obviously, summer point rainfall variability is the usual, rather than the exception, on both watersheds. Some of the storms on Alamogordo Creek, however, cover larger areas with less spatial variability than on Walnut Gulch (*19*, *20*, *31*, *36*).

Because of the relatively small differences in elevation between gages on both Walnut Gulch and Alamogordo Creek, elevation is not a major factor in explaining variation in occurrence and amounts of seasonal and annual precipitation. Other studies (*3*, *21*), however, have indicated significant variation in precipitation with elevation in the Southwest. Duckstein et al. (*3*) developed a regression equation using recording raingage records for seven summer seasons in the Santa Catalina Mountains of southern Arizona to derive a relationship for the number of rainfall occurrences (E(N)) versus elevation:

$$E(N) = 17 + 12.7\ h \qquad (r^2 = 0.88,\ SEE = 2.15)$$

where h = elevation in 1000 m.

Osborn and Davis (*21*) developed a three-parameter regional model for rainfall occurrence in Arizona and New Mexico based on 15 years of record from 22 National Weather Service (NWS) raingages. The relationship was:

$$E(N) = 333 + 15.5\ h - 3.11\ell_a - 1.97\ell_o \qquad (r^2 = 0.87,\ SEE = 2.65)$$

where ℓ_a = latitude in degrees,
ℓ_o = longitude in degrees, and
h = elevation in 1000 m.

When the latitude and longitude of the Santa Catalina raingage network were used in equation 4, the two curves were similar (fig. 23).

Duckstein et al. (*3*) found a similar relationship between summer rainfall amounts and elevation; however, there is no evidence to suggest that major runoff-producing thunderstorms in southern Arizona are more common at higher elevations than in the valleys (*32*).

SUMMER THUNDERSTORMS

The timeliness and amounts of summer rainfall are critical in the arid and semiarid rangelands of the Southwest. On a year-to-year basis, grazing capacities depend largely upon the amounts and distribution of summer rainfall in both time and space. Many forage species, particularly grasses, have evolved to take advantage of intense summer rainfall. Overgrazing and the resulting deterioration of the rangeland can result from poor judgment as to when and how much it will rain. Efforts to renovate rangelands may fail or succeed based on the amounts and distribution of convective rainfall. Furthermore, summer convective rains (thunderstorms) produce almost all runoff from arid and semiarid rangelands in the Southwest. These summer thunderstorms also produce the major flood peaks and almost all erosion from watersheds of 200 km^2 and less in the Southwest (*32*). Annual water yields and the usefulness of stock tanks and small reservoirs are based, to a large extent, on thunderstorm rainfall amounts and distribution.

Thunderstorms can occur at any time of the year in the Southwest, but are concentrated in the summer months. They are most likely to occur in the late afternoon and early evening (*30*). Airmass and frontal-convective thunderstorms are the two types of thunderstorms that dominate summer rainfall in the Southwest. Almost all Arizona thunderstorms are airmass types, whereas a significant number of frontal-convective events occur in eastern New Mexico (*46*). Frontal-convective storms tend to be more massive and last longer than airmass thunderstorms (*39*). Most rainfall in the thunderstorm season (May-September) in Arizona is concentrated in a 2-1/2 month period (July through mid-September), whereas the rainfall in eastern new Mexico is spread out (mid-April to early September). The airmass thunderstorms of 22 July, 1964, and 10 September, 1967, on Walnut Gulch are examples of the major runoff-producing airmass thunderstorms that can occur in southeastern Arizona (figs. 24 and 25). Runoff-producing rainfall lasted for less than 30 min at any raingage during the 1964 storm and less than 60 mi at any raingage during the 1967 storm. In the 1964 storm, a maximum 53 mm of rain was recorded in 30 min. In the 1967 storm, a maximum 88 mm rain was

recorded in 50 min. The area on which rainfall exceeded 50 mm was about the same for each storm, and peak discharge from Walnut Gulch was similar for both events.

The frontal-convective storms of 5 June, 1960, and 16-17 June, 1966, on Alamogordo Creek are examples of the more massive events that can occur in eastern New Mexico (figs. 26 and 27). Almost 100 mm was recorded in 1 hr at several raingages in the 1960 storm and 88 mm in 1 hr at one raingage during the 1966 event. Runoff-producing rainfall for the two events on Alamogordo Creek covered much larger areas than the two events on Walnut Gulch (fig. 28 and tables 3 and 4). For the 1967 storm on Walnut Gulch, only about half of the watershed received runofff-producing rainfall; whereas, almost the entire Alamogordo Creek watershed received runoff-producing rainfall during the 1966 storm.

The 1967 storm on Walnut Gulch occurred on the afternoon of 10 September. The first rainfall was recorded on the upper northern edge of the watershed at about 1330 at raingage RG 54 (table 3), and runoff-producing rainfall (>15 mm/hr) began at 1410. The maximum rainfall was recorded at RG 52, where 88 mm fell in 50 min (the maximum 1-hr point rainfall on Walnut Gulch in 25 years of record). The maximum 5-min intensity of 210 mm/hr was recorded at RG 44, 1.6 km from RG 52. The lower end of the watershed received only light rain near the end of the storm, with no rainfall recorded at several gages. The 1966 frontal-convective storm on Alamogordo Creek began on the evening of 16 June, at about 2320, and lasted into the morning of 17 June. Rain was first recorded on the northeast edge of the watershed, with the storm developing to the southwest (table 4). Within 30 min, runoff-producing rain was falling over the entire watershed. The maximum 1-hr rainfall, 88 mm at RG 34, was recorded between 2330 and 0030. The maximum 5-min intentsity at RG 34 was 234 mm/hr. The maximum storm rainfall was 101 mm at RG 34, and the minimum storm rainfall was 30 mm at RG 6.

Even though short-duration intensities and 1-hr amounts were similar for both events on the two watersheds, significantly more total rainfall was recorded at Alamogordo Creek. The average watershed rainfall for the two events was 3.3 x 10^6m and 11.1 x 10^6m for Walnut Gulch and Alamogordo Creek, respectively. With volumes adjusted by watershed area, almost three times as much rainfall fell on Alamogordo Creek. Several events similar to the 1966 storm have been recorded on Alamogordo Creek.

Daily Occurrence

The probability of occurrence of 0.25 mm or more of point rainfall in a day from June through September for gaged 17-, 50-, and 176-km areas on, and around, Walnut Gulch is shown in figure 29. On Walnut Gulch, thunderstorms occurred most often between 15 July and 5 August, with about a 40 percent chance of rainfall at any given point on a given day. There was a 75 percent chance of rainfall at some point on Walnut Gulch on any day during the same period. Rains were less frequent in early July, late August, and early September and seldom occurred in June or late September. Because airmass thunderstorms are limited in areal extent, there were about twice as many thunderstorm occurrences on the total Walnut Gulch watershed as at any selected point within the watershed.

Table 3.--*Accumulated rainfall (mm) for selected gages for storm of 10 September, 1967, on Walnut Gulch*

RG	1320	1330	1340	1350	1400	1405	1410	1415	1420	1425	1430	1435	1440	1445	1450	1455	1500	1510	1600
1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
4	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	1.3	2.5	6.4
5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	1.5
8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	0.5	1.3	3.3
10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	0.8
11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	2.5	5.6
13	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	3.8
14	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
18	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	0.7	--	--	--
21	--	--	--	--	--	--	--	--	--	--	--	--	--	0	1.5	2.0	2.8	4.1	5.6
23	--	--	--	--	--	--	--	--	--	--	--	0	2.0	7.9	12.7	16.8	16.8	16.8	17.3
24	--	--	--	--	--	--	--	--	--	--	--	0	3.0	6.4	7.1	7.4	7.6	7.6	7.9
28[1]																			
30	--	--	--	--	--	--	--	--	--	--	0	2.5	5.1	7.1	7.4	7.4	7.4	7.4	9.4
31	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	1.0	2.5	5.3
33	--	--	--	--	--	--	--	--	--	--	--	--	--	0	11.2	22.4	31.0	35.8	38.4
36	--	--	--	--	--	--	--	--	--	--	0	2.5	5.1	5.6	5.6	5.6	5.6	6.4	8.4
39	--	--	--	--	--	--	--	0	2.5	4.6	5.6	6.4	14.7	25.7	32.8	37.3	38.9	40.1	40.6
41	--	--	--	--	--	--	--	--	0	6.4	13.7	19.6	22.6	38.6	42.9	44.7	45.5	46.2	46.5
42	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0	13.2
43	--	--	--	--	--	0	6.1	9.7	11.4	11.4	11.7	11.9	13.0	13.2	13.2	13.5	14.0	16.0	17.0
44	--	--	--	--	--	--	--	0	3.0	5.6	11.2	20.6	25.9	37.6	55.1	68.6	72.4	73.4	73.9
45	--	--	--	--	--	--	--	--	0	4.6	12.4	20.8	28.7	34.3	38.9	43.7	45.0	46.7	48.0
47	--	--	--	--	--	--	--	--	--	0	4.1	7.4	8.9	15.7	21.3	23.6	24.1	24.4	--
48	--	--	--	--	--	--	--	--	0	0.5	1.5	2.8	3.3	3.8	4.6	5.6	5.6	5.6	5.8
*51	--	--	--	--	--	--	--	0	3.3	5.3	5.8	6.4	9.7	11.4	13.7	15.7	18.8	27.2	27.7
*52	--	--	0	0.5	0.5	0.5	0.8	6.6	14.0	19.0	25.9	34.0	43.9	55.6	68.1	80.3	86.1	87.6	--
54	0	4.1	5.1	11.4	11.4	11.9	20.6	33.0	37.3	40.1	42.4	48.0	50.3	51.6	52.6	54.6	57.9	58.4	59.9
*55	--	0	1.0	2.0	2.3	2.8	5.3	6.9	7.4	7.6	11.7	21.8	31.2	36.6	40.6	43.9	44.7	45.5	49.3
56	--	0	1.3	2.5	2.8	3.0	3.0	3.0	3.6	3.6	9.1	15.7	22.1	29.7	34.0	39.4	42.9	48.3	53.3
*57	--	--	0	2.0	2.0	2.0	2.0	2.0	6.1	16.3	22.6	32.5	38.1	42.7	45.5	46.7	48.3	49.3	50.0
60	--	--	0	0.5	2.0	2.3	2.8	2.8	2.8	8.6	24.6	32.8	34.3	39.9	43.2	45.0	45.7	47.5	48.3
65	--	--	--	--	--	0	2.0	2.5	2.8	3.0	5.8	11.2	16.3	18.3	19.6	20.8	21.8	22.9	24.4
68	--	--	--	0	2.0	2.5	2.8	2.8	2.8	3.3	5.1	7.1	8.6	9.7	10.7	11.4	11.4	11.9	--
*72	--	--	--	--	--	--	--	--	0	19.4	21.8	31.8	36.8	38.9	4.4	41.9	43.7	46.0	47.2

*Not included in 30-gage, 25-yr averages.
[1]Malfunctioned.

Table 4.--*Accumulated rainfall (mm) for selected gages for storm of 16-17 June, 1966, on Alamogordo Creek*

	16 June							17 June													
RG	2320	2330	2340	2345	2350	2355	2400	0005	0010	0015	0020	0025	0030	0040	0050	0100	0130	0200	0230	0300	0330
2	--	0	2.5	15.0	27.2	41.7	54.6	55.4	59.9	60.4	60.9	61.4	61.8	62.8	64.8	65.8	70.3	75.2	77.6	78.2	--
6	0	0.3	2.3	2.9	4.3	5.3	6.9	8.9	9.9	11.9	14.5	16.4	18.5	20.6	20.6	20.6	24.5	27.2	29.0	30.0	--
10	--	0	0.6	1.3	2.4	3.4	4.3	9.1	12.2	16.1	18.3	23.6	26.2	30.6	31.7	32.8	36.4	38.0	40.9	41.4	42.4
12	--	0	2.4	4.4	10.6	18.2	25.1	37.2	50.6	62.0	64.3	65.0	65.7	67.1	68.7	68.9	72.4	73.2	78.2	79.4	79.5
15	0	4.8	24.7	31.0	40.5	55.2	65.8	66.6	67.0	67.3	67.6	67.9	68.2	68.4	68.5	72.6	76.3	83.1	83.8	84.6	--
18	--	0	7.0	14.1	21.8	32.8	46.2	55.9	52.2	52.8	53.4	54.0	54.6	55.9	55.9	55.9	61.0	64.9	69.2	70.4	--
*20	--	0	1.5	10.4	17.2	23.6	29.7	37.3	50.7	61.6	65.2	65.6	66.0	66.8	66.8	66.8	71.5	71.6	76.7	77.7	--
21	--	0	4.9	13.6	18.4	24.1	31.0	44.0	54.8	58.2	59.2	60.2	61.2	61.8	62.5	62.5	66.3	68.6	71.6	--	--
*22	--	0	0.8	4.0	10.7	14.5	16.3	22.6	33.4	52.0	57.8	61.2	61.4	62.3	63.2	63.2	68.8	68.8	73.2	73.4	--
23	--	0	0.6	4.5	13.0	28.2	34.3	42.9	55.5	68.2	73.9	74.3	74.7	75.5	76.3	77.2	82.0	84.3	86.5	87.6	--
25	0	0.2	0.6	1.2	3.0	4.1	5.1	10.8	17.0	20.9	25.7	39.9	43.1	46.8	48.0	49.3	54.6	55.9	59.0	60.5	--
26	0	1.5	1.9	2.1	2.3	3.3	4.3	5.2	10.1	15.0	26.7	31.2	36.1	37.7	39.2	40.6	47.0	47.8	50.5	51.6	--
*33	0	0.5	1.7	2.4	11.1	25.0	38.6	51.4	57.5	71.4	77.0	77.9	78.8	80.6	82.5	82.7	89.2	89.2	90.7	91.3	--
*34	--	0	2.0	4.8	16.0	24.6	33.3	46.5	66.0	76.0	85.9	88.1	88.4	89.4	90.1	91.0	96.2	97.0	98.4	101.1	--
35	--	0	5.4	12.6	17.4	19.8	19.8	42.4	58.5	63.1	63.7	64.4	65.5	65.6	66.0	66.3	67.1	68.3	72.9	73.7	--
37	0	0.9	10.3	16.6	20.4	24.9	34.0	41.4	49.9	51.8	52.3	52.8	53.1	53.1	53.1	53.1	54.5	55.8	59.7	60.7	--
43	0	2.4	16.5	22.0	28.0	34.0	49.8	51.3	52.8	53.2	53.7	54.2	54.5	54.6	54.7	54.9	55.1	58.7	60.2	61.0	--
*44	0	0.4	1.8	7.3	16.8	22.6	24.9	35.8	53.7	63.0	63.8	64.5	64.6	64.7	64.8	65.0	66.7	70.1	750	75.9	--
45	0	0.2	3.4	13.4	23.7	30.4	32.3	46.1	60.1	68.4	73.0	73.2	73.4	73.8	74.0	74.4	74.9	75.4	79.8	83.1	--
47	--	0	0.1	0.2	0.5	8.1	15.7	21.0	25.8	31.6	38.6	46.0	46.3	46.9	47.5	47.5	47.5	47.5	48.5	51.1	--
49	--	--	0	0.3	0.9	2.0	5.8	14.2	19.6	24.0	25.2	30.5	31.9	32.8	33.8	34.3	34.8	35.1	37.2	38.1	--
53	--	0	0.4	0.8	1.3	5.1	18.5	24.8	30.2	45.8	54.6	56.5	56.9	57.3	57.7	58.2	58.5	58.5	62.5	64.5	--
55	0	1.0	4.3	15.6	30.5	38.1	41.1	52.8	61.2	66.4	66.8	67.2	67.6	68.8	69.2	70.2	71.1	72.4	76.5	78.7	--
57	0	1.0	10.7	23.7	30.1	31.6	34.3	36.3	37.0	37.7	38.4	38.8	39.2	39.5	39.5	39.5	39.6	43.1	44.4	45.7	--
59	0	1.6	9.7	17.3	23.6	26.8	28.2	28.4	28.7	28.9	29.2	29.8	30.6	31.5	31.5	31.5	31.5	35.6	38.2	38.6	--
63	--	0	2.5	4.1	11.9	20.4	27.7	32.7	38.4	41.1	42.5	43.3	44.1	44.6	45.0	45.0	45.4	48.0	52.8	54.9	--
65	--	0	0.2	0.8	4.9	16.8	29.0	38.0	45.0	48.6	50.2	50.7	51.2	53.1	53.2	53.3	54.0	55.8	61.9	63.8	--
67	--	0	1.0	7.9	24.3	33.1	41.9	47.4	53.4	58.9	59.3	59.8	60.2	60.8	61.0	61.0	61.8	65.8	70.6	72.6	--
74	--	0	0.7	3.7	13.3	21.9	31.2	40.9	43.4	44.1	48.3	48.8	49.5	50.6	50.8	50.8	55.1	65.5	69.4	71.1	--
76	--	0	1.7	5.1	14.2	24.4	36.6	40.4	44.4	47.1	48.2	48.6	49.1	51.1	51.1	51.1	55.9	63.5	67.4	69.1	--
78	--	0	3.7	8.7	16.3	24.6	38.1	42.6	44.3	45.0	45.7	45.9	46.2	46.7	46.7	46.7	48.4	56.4	62.6	64.3	--
80	--	0	1.0	3.3	11.2	23.6	32.8	37.8	39.4	41.4	41.7	42.9	43.0	43.2	43.3	43.4	49.6	54.2	57.2	59.2	--
83	--	--	--	--	0	3.8	7.6	15.9	18.7	21.2	23.1	24.7	24.9	25.1	25.5	26.0	26.4	32.2	34.6	37.8	38.4
89	--	--	0	0.8	2.0	7.8	13.5	26.9	30.1	38.6	41.1	46.4	46.8	47.2	47.5	47.9	48.3	50.4	54.6	56.1	--
94	--	--	--	0	0.3	0.7	2.8	9.0	14.8	20.4	26.1	32.8	37.4	39.8	40.6	40.8	41.0	46.2	50.4	52.3	54.4

*Not included in 30-gage, 23-yr averages.

Assuming rainfall occurred randomly within the area, a relationship (unpublished until now) between point and area occurrences was developed for ungaged watersheds:

$$P_A = 1 - (1-P_p)^{A^a}$$

where A = area in km^2 ($1 \leq A \leq 200$),
P_A = probability of 0.25 mm or more rain somewhere within the area,
P_p = probability of 0.25 mm or more rain at a point within the area, and
a = regional variable (a = 0.16 based on Walnut Gulch data).

Actual and predicted probabilities are shown in table 5.

Table 5.--*Comparison of actual and predicted (equation 5) rainfall probabilities ($\geq$ 0.25 mm) for given areas and periods on Walnut Gulch*

	July 1-15		July 16-31		Aug. 1-15		Aug. 16-31		Sept. 1-15	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
Point	0.24	---	0.47	---	0.32	---	0.28	---	0.24	---
17-km^2	.35	0.35	.58	0.63	.45	0.46	.37	0.40	.34	0.35
50-km^2	.42	.40	.66	.70	.53	.51	.46	.46	.40	.40
176-km^2	.52	.47	.78	.77	.63	.59	.51	.53	.48	.47

Note: For Walnut Gulch, a = 0.16.

The probabilities of occurrence for rainfall equal to or exceeding 5 mm and 15 mm are shown in figures 30 and 31. At any point within the Walnut Gulch watershed, about one-half of all summer events equals or exceeds 5 mm, and about one-quarter exceeds 15 mm. For storms of 15 mm or greater, occurrences on the 50- and 176-km^2 watersheds differ significantly. Without the curves in figures 29 to 31, single gage records are not adequate for estimating the number of runoff events in a southwestern rangeland watershed. From equation 5, good probability estimates are possible for 5-mm and 15-mm storms as well as 0.25-mm events.

In eastern New Mexico, the thunderstorm season is spread over several more months than in southeastern Arizona. Thunderstorms, either airmass or frontal convective, are most common in July, but the season may begin as early as April and last into September (fig. 32). Probabilities for 0.25 mm or more of rainfall never exceed 50 percent. There is about a 25 percent chance of rain at any given point on Alamogordo Creek on any given day in July. There is about a 45 percent chance that there will be rainfall some place on the 174-km^2 watershed on any day

during the same period. Thunderstorm rainfall probabilities increase gradually starting in mid-April, peak in July, and decrease through August into early September.

Actual and predicted probabilities, based on equation 5 (a = 0.16), are shown in table 6. At the peak of the season (July and August), the equation gives a good estimate, but rainfall probabilities are overpredicted in April, May, June, and September.

Table 6.--*Comparison of actual and predicted (equation 5) rainfall probabilities ($\geq$ 0.25 mm) for given areas and periods on Alamogordo Creek*

	May		June		July		August	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
Point	0.12	---	0.17	---	0.23	---	0.19	---
13.5 km^2	.14	0.18	.20	0.25	.29	0.33	.27	0.27
61 km^2	.18	.22	.25	.30	.37	.40	.33	.33
174 km^2	.20	.25	.32	.35	.45	.45	.40	.38

These analyses suggest that most thunderstorms on Alamogordo Creek are similar to those on Walnut Gulch. The large majority of thunderstorms on Alamogordo Creek are either pure airmass events or events in which frontal activity is too weak to increase the areal extent appreciably; however, major events on Alamogordo Creek cover much larger areas than major events on Walnut Gulch. Furthermore, a plot of maximum annual 1-hr point rainfall (fig. 33) indicates that greater point depths on Alamogordo Creek are not annual occurrences. Therefore, the occasional massive frontal-convective events in eastern New Mexico should be treated as an unusual and separate population of storms.

The probabilities of occurrence for summer rainfall equal or exceeding 5 and 15 mm are shown in figures 34 and 35. There were twice as many significant and runoff-producing rains on the entire Alamogordo Creek watershed than are indicated at any point within the watershed. The number of seasonal occurrences on Alamogordo Creek, however, was appreciably less than for Walnut Gulch, indicating that the occasional major frontal-convective event on Alamogordo Creek must influence average point-to-area occurrence ratios for storms within greater point depths.

Storm Frequency

Several studies have been on the frequency of rare events and high-intensity rainfall in the Southwest. Based on 22 years of record, from nine and five 12-hr

recording raingages on the Safford and Montana watersheds, respectively, Osborn and Reynolds (*37*) determined occurrence frequencies of high-intensity, short-duration rainfall. Osborn (*20*) developed depth-frequency relationships for 30 and 60-min durations for Walnut Gulch and Alamogordo Creek (fig. 36). The relationships included expected values for both point and total watershed area. Osborn and Lane (*27*) quantified these relationships in developing point-area-frequency conversions for summer rainfall in southeastern Arizona. The occurrence of infrequent exceptional events has been assumed random in the studies. Furthermore, there is no evidence that such events within a region are affected by elevation or other watershed parameters (*32*).

Persistence (Wet and Dry Periods)

The climate of the Southwest might be characterized as dry with intermittent precipitation. Precipitation is not likely to occur in certain seasons, and range forage is adapted to this. Spring droughts are common on Walnut Gulch. In 15 of the 25 years of record, less than 15 mm of precipitation was recorded on Walnut Gulch from March through June. The longest period without rain was 5 months in the spring of 1972. Maximum and minimum point rainfall for periods of 1 month to 3 years illustrates the differences that occur on Walnut Gulch and Alamogordo Creek from season to season and year to year (tables 7 and 8).

Osborn (*22*) studied the persistance of Walnut Gulch summer rains and drought periods, and found that summer rainfall, although highly variable, represented the most dependable source of water to the Walnut Gulch watershed. On the average, significant rainfall was recorded on some part of the watershed on 40 percent of the days in July and August. The maximum frequency was 3 out of every 4 days in 1955, and the minimum, 3 out of every 10 days in 1960. The longest summer drought during the period of record (1956-80) occurred in 1962, when no rain fell for 17 days in August following a 14-day rainy period in late July.

Smith and Schreiber (*52*), using data from three scattered raingages in the region, computed the discrete series of daily Bernouli parameters and daily first-order Markov transistion probabilities. They tested the hypotheses of sequential independence versus a first-order Markov dependence hypothesis for random variables, including wet and dry run lenths, occurrence of the first wet day of the season, number of runs per season, and total number of rainfall days per season. They found that the Markov chain model was superior to the Bernoulli model, but that year-to-year variations in the process require additional probabilistic descriptions indicated by annual variance in the number of rainy days and significant annual changes in autocorrelation properties.

WINTER PRECIPITATION

Very little research has been carried out on winter precipitation in the southwestern United States; however, winter precipitation in this area is an important source of rangeland moisture for spring growth of many species of grasses, shrubs, and forbes grazed by livestock (*24*).

Table 7.--*Maximum and minimum point monthly and seasonal precipitation (mm) for Walnut Gulch (WG) (1956-80) and Alamogordo Creek (AC) (1956-78)*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Oct.-Apr.	Annual
WG:															
Max.	83	52	91	36	33	109	204	196	166	104	44	112	377	288	482
Min.	0	0	0	0	0	0	16	0	0	0	0	0	62	15	118
Mean	17	12	14	4	3	8	80	68	34	20	10	18	193	95	288
AC:															
Max.	32	25	64	69	204	199	269	220	121	132	63	73	549	243	736
Min.	0	0	0	0	0	0	5	0	0	0	0	0	58	6	99
Mean	6	8	10	13	25	40	76	60	32	26	10	9	233	82	315

Table 8.--*Maximum and minimum point precipitation (mm) selected durations form 1 to 36 months on Walnut Gulch (WG) (1956-80) and Alamogordo Creek (AC) (1956-78)*

	1	2	3	4	5	6	7	8	9	10	11	12	18	24	36
WG:															
Max.	204	324	377	379	412	436	438	471	493	557	558	627	825	952	1278
Min.	0	0	0	0	0	9	20	22	28	41	61	96	161	305	552
AC:															
Max.	269	437	475	520	613	628	654	669	672	680	713	741	1083	1149	1497
Min.	0	0	0	0	3	6	6	8	28	35	54	54	123	228	441

Winter rainfall in Walnut Gulch and Alamogordo Creek (tables 1 and 2) differed significantly. Runoff-producing summer rains may occur as late as early October on Walnut Gulch; whereas, few summer events have been recorded later than early September on Alamogordo Creek. Winter precipitation was concentrated in December and January on Walnut Gulch, and was more evenly spaced from November through March on Alamogordo Creek. Low intensity precipitation and thunderstorm rains were recorded on both watersheds in April, but winter events were more common. Spring forage on Walnut Gulch relied on winter precipitation. On Alamogordo Creek, spring rains provided significant moisture for plant growth. On Walnut Gulch, less than 10 percent of winter precipitation is snow (*31*), whereas snow accounted for at least 50 percent of the winter precipitation on Alamogordo Creek (*1*).

Osborn et al. (*24*) observed that winter precipitation on both Walnut Gulch and Alamogordo Creek seemed to be at least as variable from year to year as summer precipitation. They also determined that a well-spaced eight-gage network would be satisfactory for analysis of Walnut Gulch winter storms on a per-storm basis, and because of the larger areal extent of most winter storms, one raingage probably could be used to give an accurate estimate of annual winter precipitation on either watershed.

There is little evidence of increased winter precipitation with increased elevation on either Walnut Gulch or Alamogordo Creek (figs. 15 and 16). Furthermore, there was no evidence of increased precipitation with elevation for major winter events on Walnut Gulch (*24*).

MODELING

Many early research papers based on Walnut Gulch data were concerned with difficulties in modeling the thunderstorm rainfall/runoff process. Infiltration data were insufficient for predicting surface runoff (*8*) and the effects of rainfall on soil surface characteristics were uncertain (*11*). Hydrologically similar unit-source watersheds were instrumented to answer some of the questions raised by differences in onsite and watershed runoff (*10*). The significance and precision of estimated parameters for runoff were determined (*29*), and methods were suggested for improving point prediction from available data (*42*, *43*). The accuracy of point estimates, based on nearby gage records, was studied (*50*), and limitations were suggested for predicting peak discharge from other than maximum short-duration rainfall intensity (*25*, *40*).

Rainfall Probability

The first attempt at modeling the probability of thunderstorm rainfall occurring during the summer rainy season was based on 10 years of Walnut Gulch data, and the occurrence or nonoccurrence of an event was modeled as a Bernoulli variable, with changing probability through the season (fig. 37).

In a more recent paper (*21*), Walnut Gulch and NWS data were used to develop a three-parameter occurrence model for Arizona and New Mexico. Daily rainfall probabilities for base stations in three subregions were determined, and the rainfall probabilities for selected stations were estimated based on their latitude, longitude, and elevation.

Smith and Schreiber (*53*), in a sequel to their earlier work (*56*), studied daily rainfall depth probabilities. They particularly looked at the conditional distribution of rainfall depths given the occurrence of rain. They found that the variability of annual rainfall depth is due more to variability of storm depth than to the number of rainy days in a season. They found that daily rainfall depths were well described by a compound exponential distribution and stated that their study should lead to more useful work in the field of rainfall depth probabilities. Others have also concluded that such advances can, and should, be made (*2*, *12*, *21*, *28*, *33*, *38*).

Depth-Area Relationships

Several investigators (*9*, *26*, *34*, *37*) identified depth-area relationships for major thunderstorm events in the Southwest. Keppel (*9*) and Osborn and Reynolds (*37*) described an exceptional event (5 June, 1961) on Alamogordo Creek with depth-area relationships showing the relatively large extent of runoff-producing rainfall. Osborn and Reynolds (*37*) also developed depth-area-duration curves for a violent hail storm (13 July, 1961) on Alamogordo Creek. Osborn and Renard (*35*) developed depth-area curves for two major airmass thunderstorm events on Walnut Gulch (22 July, 1964, and 10 September, 1967).

Some of the earliest efforts in modeling thunderstorm rainfall were to develop generalized depth-area relationships (*16*, *26*, *57*). Woolhiser and Schwalen (*57*) and Fogel and Duckstein (*6*) devleoped thunderstorm rainfall models based on data from a network of 29 recording raingages on the University of Arizona's 50-km Atterbury watershed near Tucson, Ariz. Woolhiser and Schwalen based their equation on 3 years of record, pointing out that the maximum event had a 65-mm center depth. Fogel and Duckstein assumed a Gaussian distribution and developed their equation from 12 years of record on the same watershed. The U.S. Weather Bureau, in a report prepared for the U.S. Army Corps of Engineers (*55*), presented depth-area-duration curves for probable maximum precipitation based on selected exceptional events in the Southwest. Osborn and Lane (*26*) developed a depth-area relationship with data from Walnut Gulch based on the criteria: (1) depth of rainfall covering 2.6 km^2 is 90 percent of the maximum point rainfall, (2) the rainfall depth decreases logarithmically with increasing area covered, and (3) the areal extent of airmass thunderstorm rainfall is finite.

The five depth-area equations are summarized below in similar notation:

Osborn-Lane: $$D = D_o\,[0.9 - 0.2\ \ln (\frac{A}{2.6})], \qquad 2.6 \leq A \leq 230$$

Fogel-Duckstein: $D = D_o\, e^{-\frac{Ab}{2.6}}$

where $b = 0.27e^{-\frac{0.67\, D_o}{25.4}}$

Woolhiser-Schwalen: $D = D_o - 110 \log_{10} \frac{A}{2.6} - 17.5$

USWB, 3-hr storm: $D = D_o\left(1- \sqrt{\frac{A}{0.132}}\,/100\right)$, $2.6 \leq A \leq 230$

USWB, 1-hr storm: $D = D_o\left(1- \sqrt{\frac{A}{0.083}}\,/100\right)$, $2.6 \leq A \leq 230$

where

D = depth of rainfall (mm),
D_o = depth of rainfall at storm center (mm), and
A = area covered by D and greater rainfall (km^2).

The five relationships were compared for a storm with a center depth of 50 mm (fig. 38).

Smith (*51*) established a general relation between randomized storm isohyetal pattern, center depth probability, and point rainfall probability and used this relationship to test the consistency of published depth-area relationships. Figure 39 shows the dimensionless reductions of several depth-area relationships included in figure 38 (*6*, *26*, *57*).

Finally, Osborn et al. (*31*), in cooperation with the NWS, developed depth-area conversion curves from 20 years of data from the Walnut Gulch and Alamogordo Creek raingage networks for adjusting point rainfall amounts to supplement information available in National Oceanographic and Atmospheric Administration (NOAA) Atlas 2 (*15*). The curves varied considerably between the two climatic zones represented, as well as with differing frequencies, but very little with storm duration (figs. 40 and 41). In southeastern Arizona, at Walnut Gulch, the reductions from point to area were significantly greater than curves published in NOAA Atlas 2, which is consistent with known area characteristics of runoff-producing airmass thunderstorms (*31*, *32*).

Curves based on Alamogordo Creek data (*31*) varied less from the NOAA Atlas 2 relationships, suggesting the Alamogordo Creek data were similar to regional data used in the NOAA analysis.

USLE "R" Factor

Several investigators have noted the effect of thunderstorm rainfall intensities and variability on the "R" factor in the Universal Soil Loss Equation (USLE) (*41*, *47*, *48*). The USLE was developed for cultivated agricultural areas of the eastern United States and has been considered for use in the West (*56*). The "R" factor is the average number of erosion-index (EI) units in a year's rainfall, or the EI units in an individual storm if the equation is used to predict individual storm erosion. The EI units are determined by multiplying the total kinetic energy of the rainfall times the maximum 30-min intensity. Obviously, in the Southwest, where most runoff-producing events last less than 30 min and are extremely variable in both time and space, the proper estimation of the "R" value is essential in using the USLE (*47*, *48*). In fact, the variability of the "R" factor between storms is an order of magnitude greater than the variability of rainfall between storms.

Several conclusions have been reached in regard to use of the USLE in southwestern Arizona (*48*): (1) short records from a single precipitation gage can be used for individual events or for annual estimates, but only within a short distance of the gage, (2) short time intervals must be used to obtain an accurate estimate of the EI, and (3) additional work is needed to facilitate estimating the EI value from the precipitation data available in most areas of the Southwest.

Independent Sampling Points

The relative dependence of individual rain sampling points is important in the development and verification of rainfall occurrence models (*16*, *28*). Analyses have been carried out on the correlation between recording raingages for individual storm events. Osborn et al. (*28*) investigated the correlation between gages from maximum 15-min and total storm rainfall on Walnut Gulch and concluded that, for $r \geq 0.9$, gages must be spaced no further than 300 and 500 m apart, respectively. This analysis inferred that gages at some greater spacing might be considered as independent sampling points.

Osborn et al. (*36*) calculated correlation coefficients between gages for total storm rainfall amounts from thunderstorms on Walnut Gulch and Alamogordo Creek (fig. 42). By using storm totals, they assumed that time variability had been eliminated and that the simple correlations would be a useful indication of spatial variability. The relationship between correlation coefficient (r) and distance between pairs of gages decreased more rapidly for Walnut Gulch than Alamogordo Creek. The study suggested that for evaluation of extreme events on Walnut Gulch, gages separated by at least 6 km could be considered as independent sampling points, and because of the larger areal extent of some frontal-convective events in eastern New Mexico, gages must be 12 km apart to be considered independent sampling points. A more recent study (*20*), which included comparison of maximum shorter duration rainfall amounts between pairs of gages, again suggested that relatively closely spaced gages in southeastern Arizona could be considered as independent sampling points.

Regional Model

The first comprehensive watershed rainfall model (*32*), developed in the early 1970's, was based entirely on Walnut Gulch rainfall data. Probability distributions were used to model random variables (number of cells, spatial distribution of the cells, and cell center depths) of thunderstorm rainfall in a summer season. A computer program produced synthetic thunderstorm rainfall based on these distributional assumptions (fig. 43) and, as mentioned earlier, on a Bernoulli random variable (fig. 44). The combined program, CELTH (cell thunderstorm), was considered a simplified stochastic model of airmass thunderstorm rainfall. Uncertainties in estimating the runoff-producing rainfall of thunderstorm rainfall models were pointed out, and the importance of the assumption of stationarity in such modeling was stressed (*16*).

Smith (*51*), in the third of a series of three papers on point processes of seasonal thunderstorm rainfall, reported the relationships of point rainfall to storm area properties. His results suggested that the CELTH model could be improved significantly. For one thing, the CELTH Model was more respresentative of the major runoff-producing events rather than of the more common smaller rainfall occurrences. To evaluate storm relationships, Smith developed a general relationship between storm depth and area as well as distributions for point and storm center depths. He concluded that more extensive data were needed on dimensionless depth-area relationships and center-depth distributions to understand dependencies between storm shape and storm cell depth.

More recently, the early CETH model was revised and combined with the regional rainfall occurrence model (*21*) to develop a comprehensive regional rainfall model, SATDOR (Space and Time Distribution of Rainfall), for Arizona and New Mexico (*38*). The model simulates rainfall occurrence and amounts on a per-storm basis for ungaged watersheds up to 150 km^2 with elevations between 300 and 2300 m in Arizona and New Mexico. The model is a compilation of many subroutines with a number of alternative inputs and outputs. The output includes accumulated seasonal rainfall for any designated point, point totals for individual events for isohyetal mapping, starting and ending times for all simulated events, the seasonal distribution of the events, and Thiessen weighted watershed averages for all events. The output can be used directly to estimate runoff peaks and volumes for watersheds less than 100 ha and indirectly for larger watersheds with appropriate routing methods. Since the rainfall is distributed both in time and space, simulations of several years of record can be used to provide probabilities of wet and dry sequences to evaluate the chances of success for range renovation programs and can aid ranchers in overall planning of range management programs.

The current model is an improvement over the earlier model(s), but is still based on runoff-producing events and may not be representative of the full spectrum of storms. The intrastorm relationships are lumped into gross parameters, and there is still room for improvement in the point-to-area rainfall relationships. SATDOR is an accumulation of subroutines that are being continually improved. The program is available from the authors.

SUMMARY AND CONCLUSION

Research at the SWRWRC on precipitation characteristics in the Southwest can be divided into several efforts. Early efforts were primarily to identify the unusual features of summer convective rainfall and show the variability in time and space with documentation of individual runoff-producing rains. A complimentary effort, which still continues, was to develop seasonal and annual means and ranges of precipitation along with the spatial variability in such values. The ongoing effort is based on two premises. First, there was the need to accurately measure rainfall input to the complex rangeland watersheds and be able to study the distribution and quality of the water that moved over and was involved in the watershed hydrologic cycle. Second, sufficient precipitation information was needed to be able to transfer what we had learned to ungaged watersheds. This effort has resulted in developing point-to-area and depth-area-frequency relationships that can be used in similar climatic regions.

Our principal effort, in recent years, has been to develop precipitation models. Other efforts have included revision or improvement in methods or models that were not originally designed for use in areas where the climate is dominated by thunderstorm rainfall, as it is in the Southwest. Further modeling research efforts are needed to answer questions regarding intrastorm variabilities, possible cycles and trends, and the role of elevation and other topographic features on rainfall amounts and distributions.

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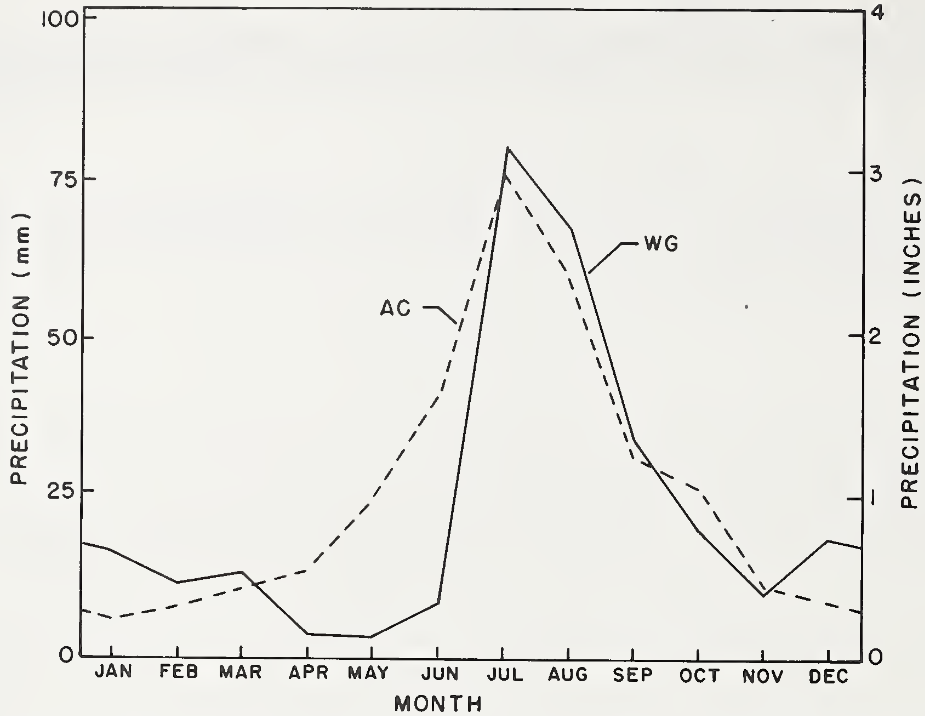

Figure 2.--Mean monthly precipitation for Walnut Gulch (1956-80) and Alamogordo Creek (1956-78).

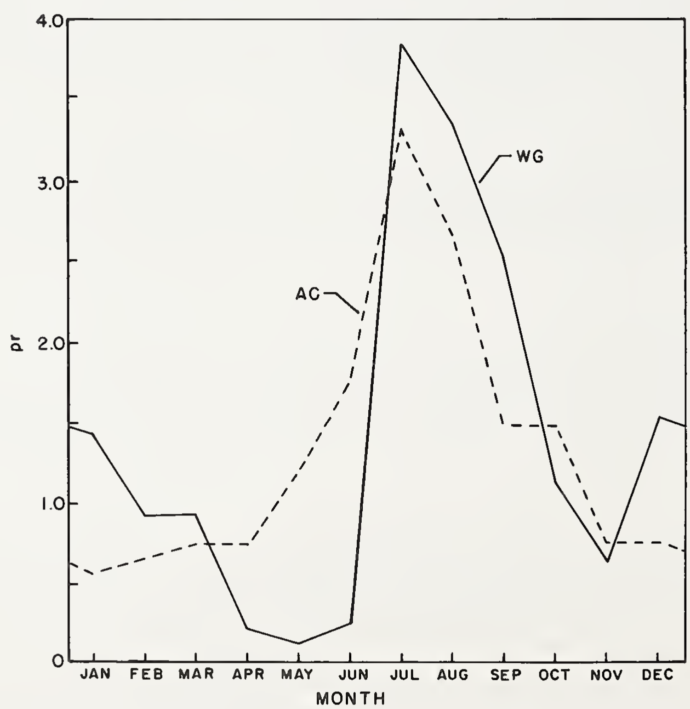

Figure 3.--Precipitation effectiveness monthly values for Walnut Gulch and Alamogordo Creek.

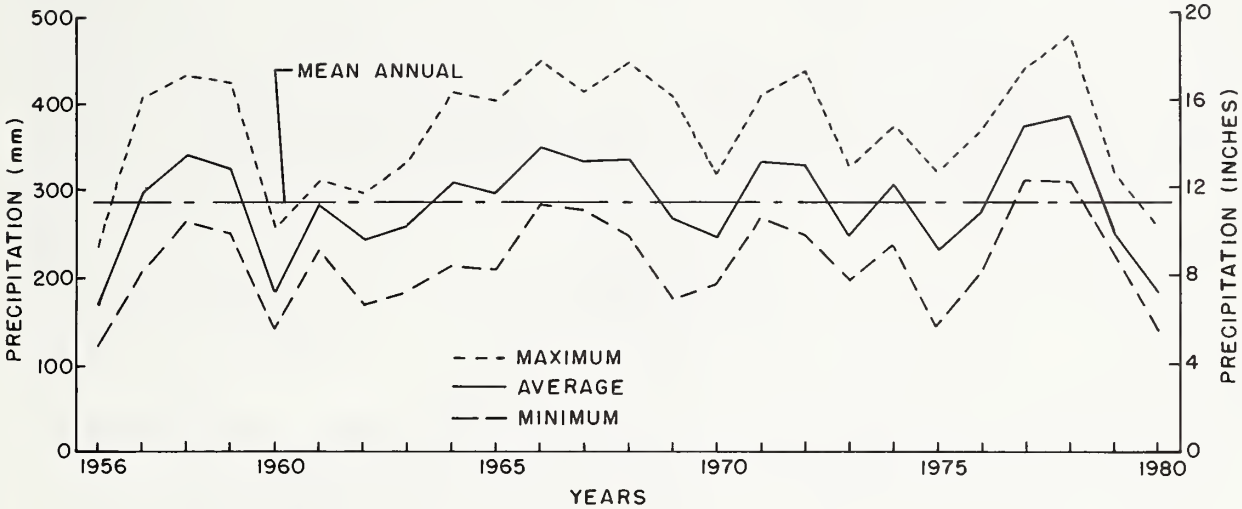

Figure 4.--Watershed average and maximum and minimum annual point precipitation for Walnut Gulch.

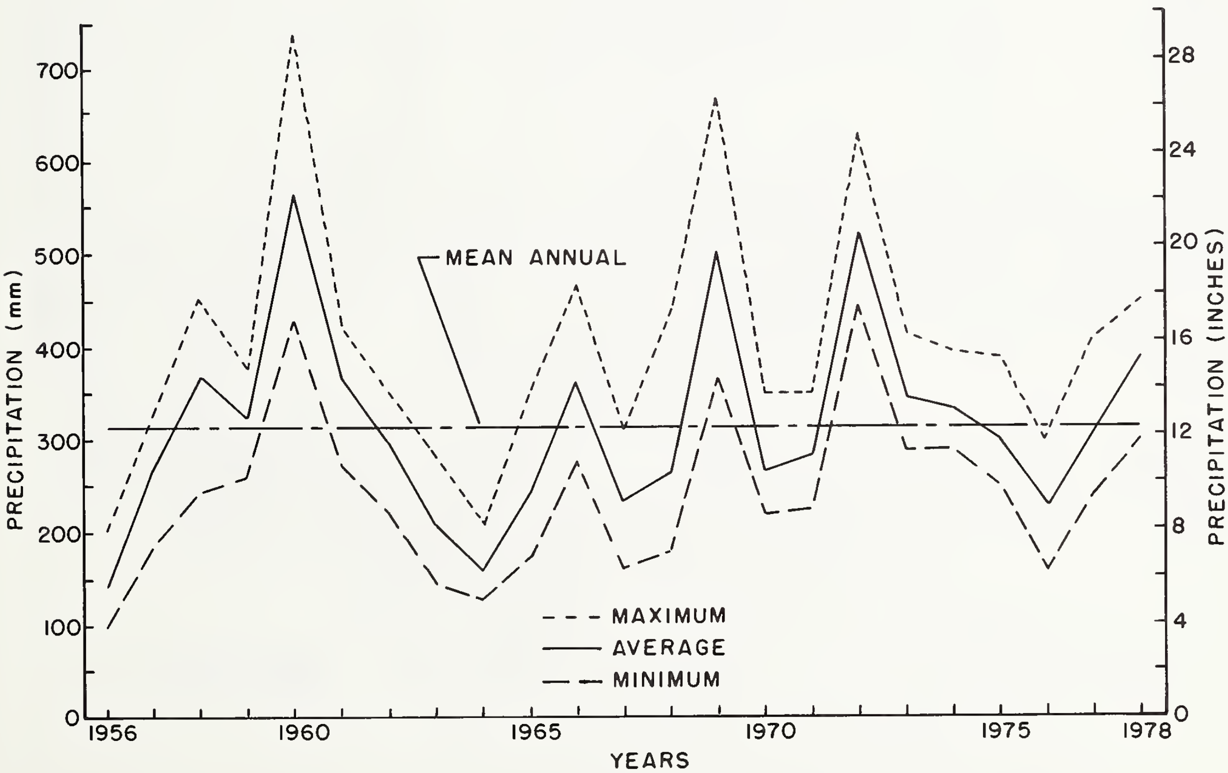

Figure 5.--Watershed average and maximum and minimum annual point precipitation for Alamogordo Creek.

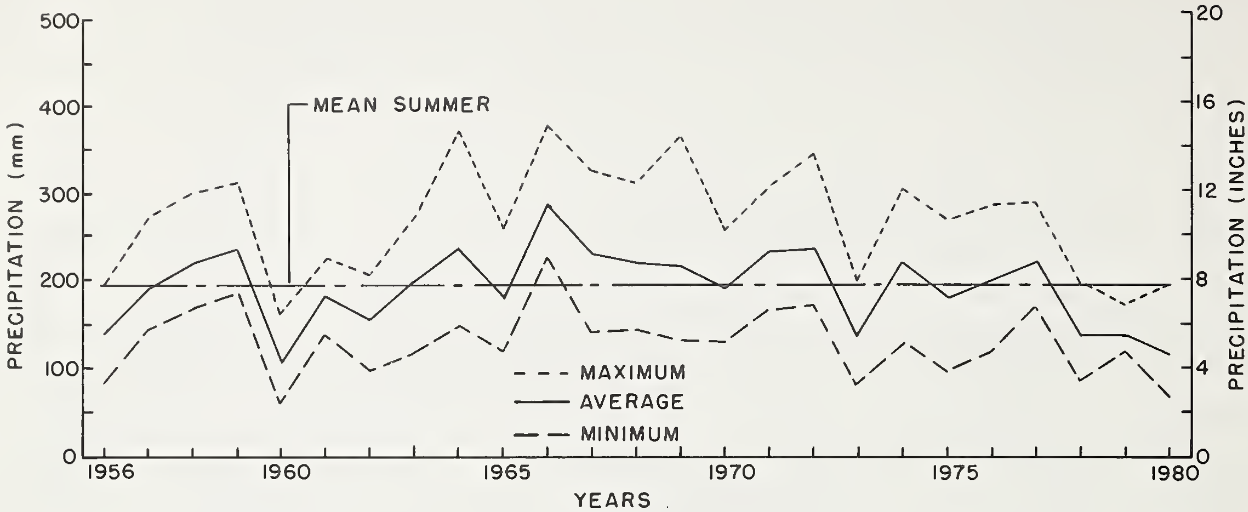

Figure 6.--Watershed average and maximum and minimum summer (May-September) point precipitation for Walnut Gulch.

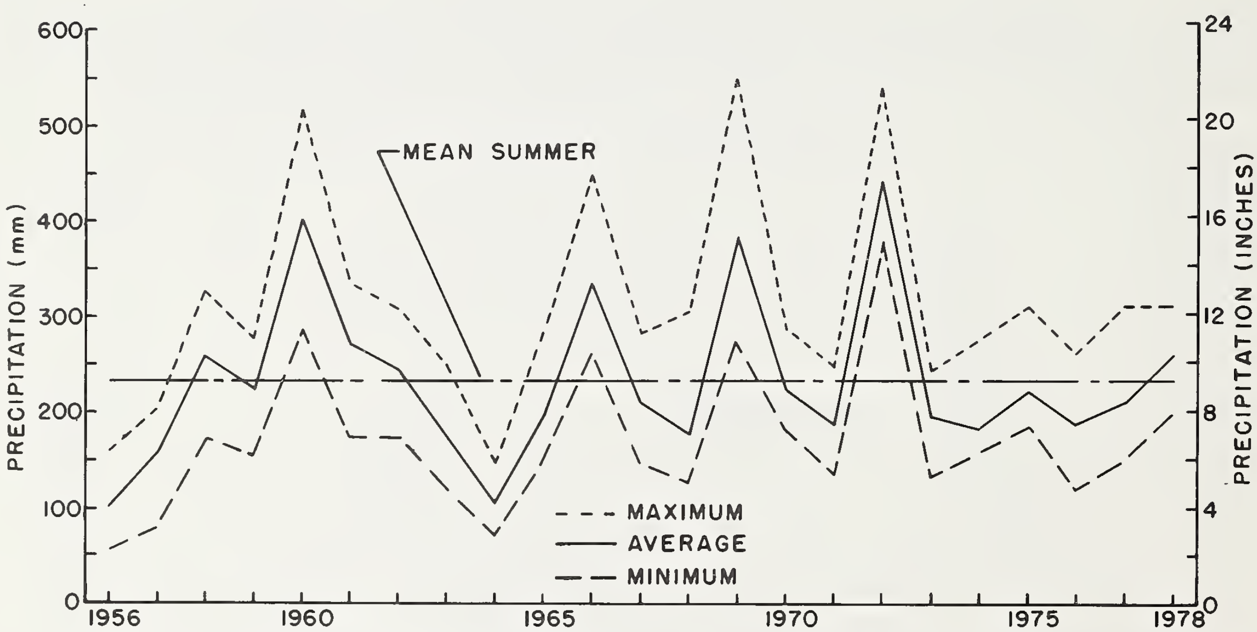

Figure 7.--Watershed average and maximum and minimum summer (May-September) point precipitation for Alamogordo Creek.

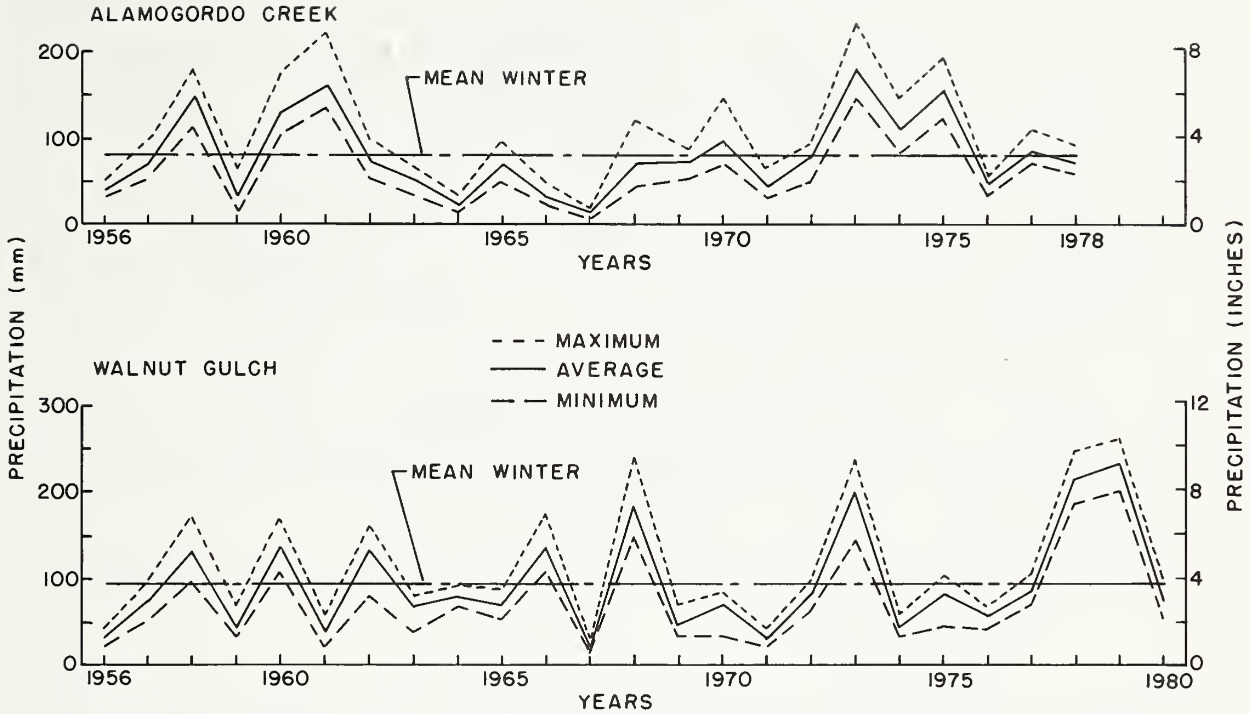

Figure 8.--Watershed average and maximum and minimum winter point precipitation for Walnut Gulch and Alamogordo Creek.

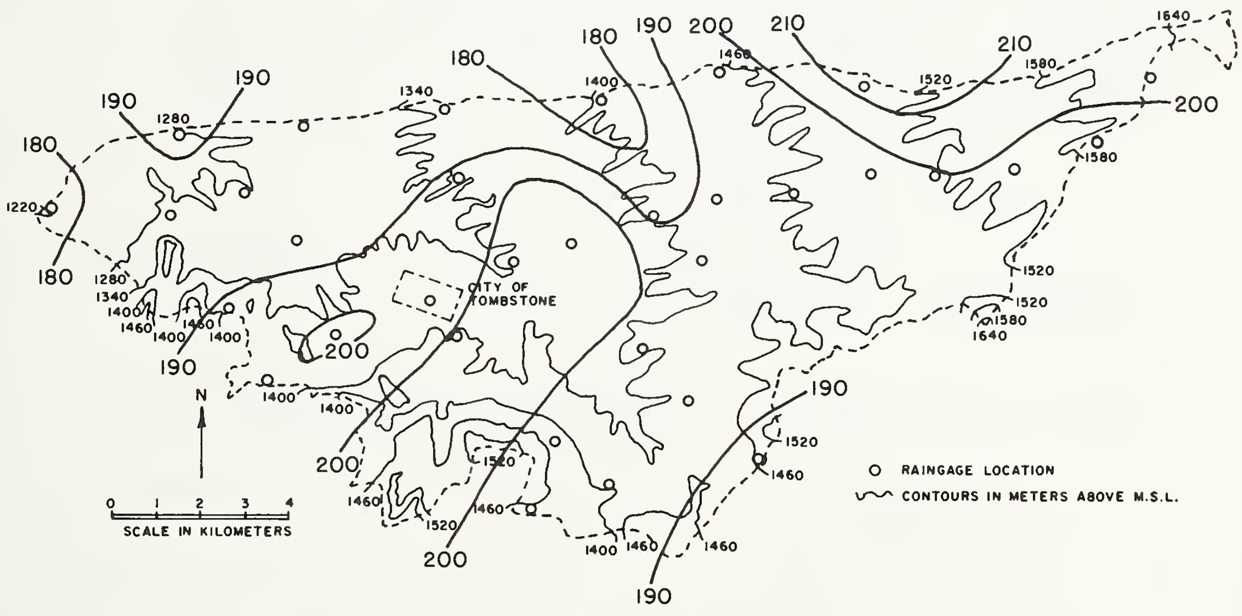

Figure 9.--Mean summer rainfall (mm) on Walnut Gulch (1956-80).

Figure 10.--Mean winter precipitation (mm) on Walnut Gulch (1956-80).

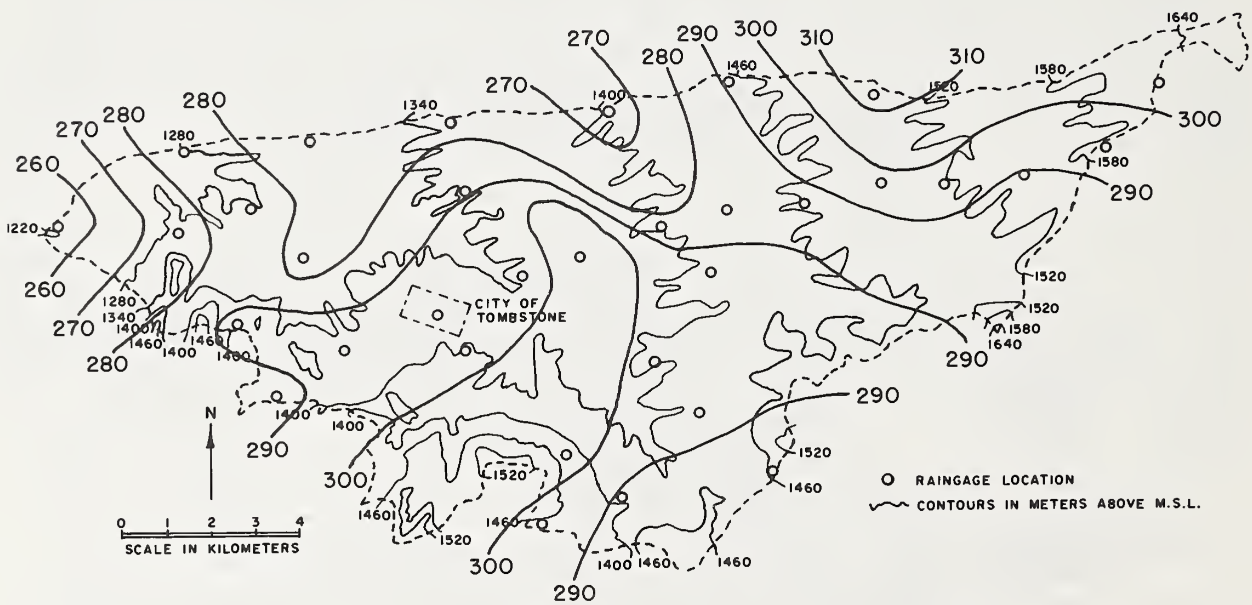

Figure 11.--Mean annual precipitation (mm) on Walnut Gulch (1956-80).

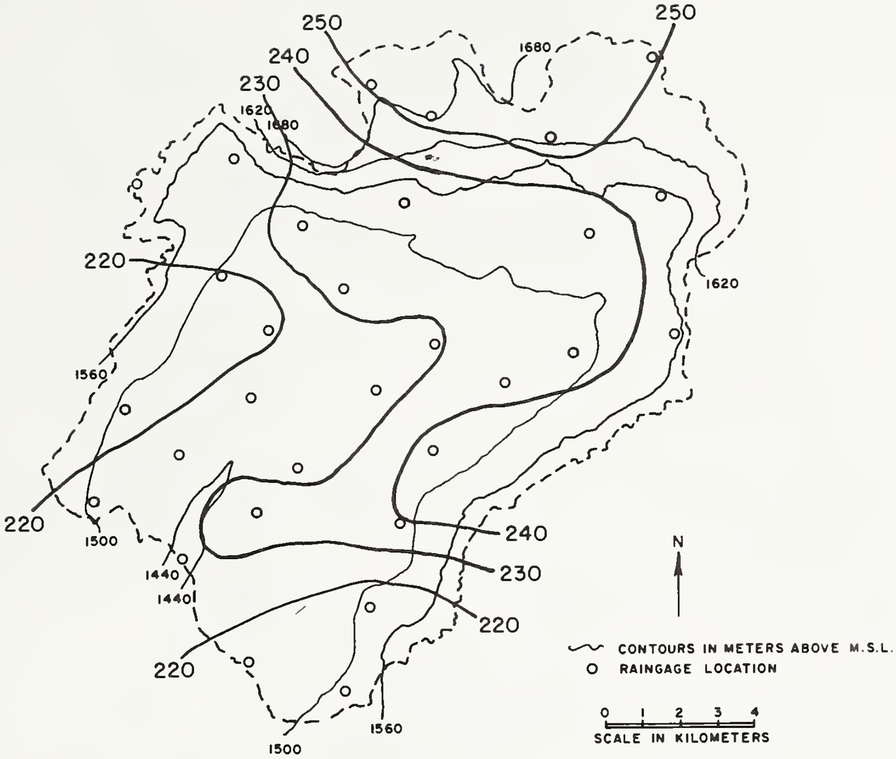

Figure 12.--Mean summer rainfall (mm) on Alamogordo Creek (1956-78).

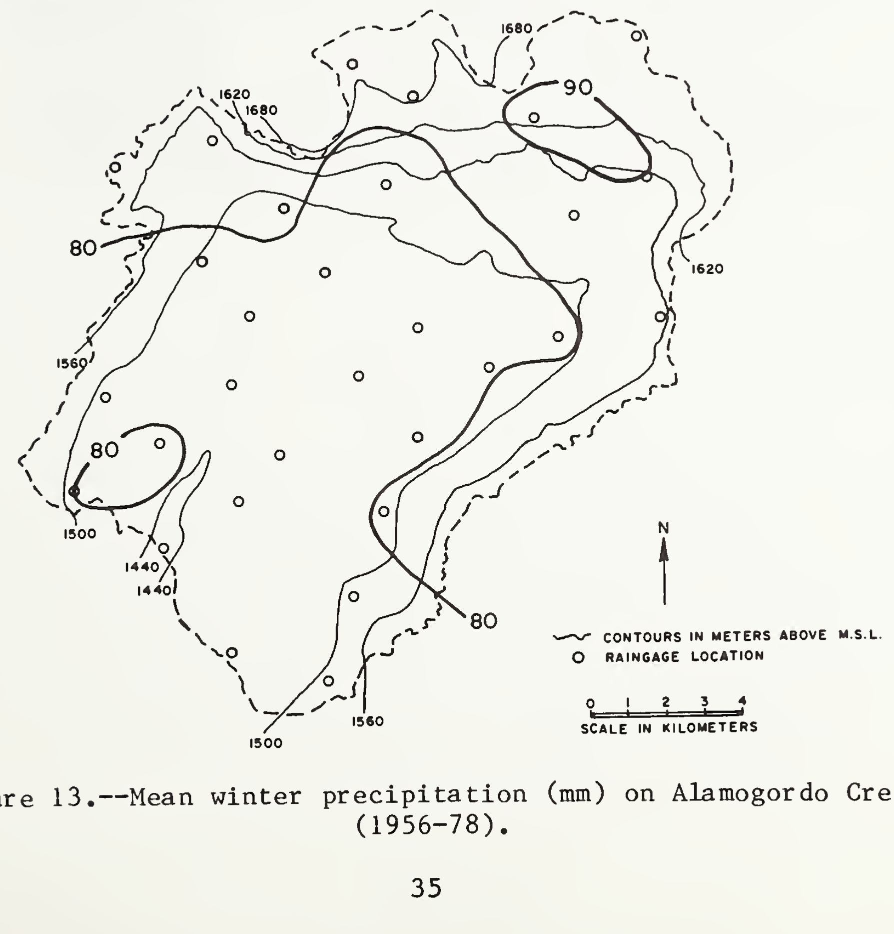

Figure 13.--Mean winter precipitation (mm) on Alamogordo Creek (1956-78).

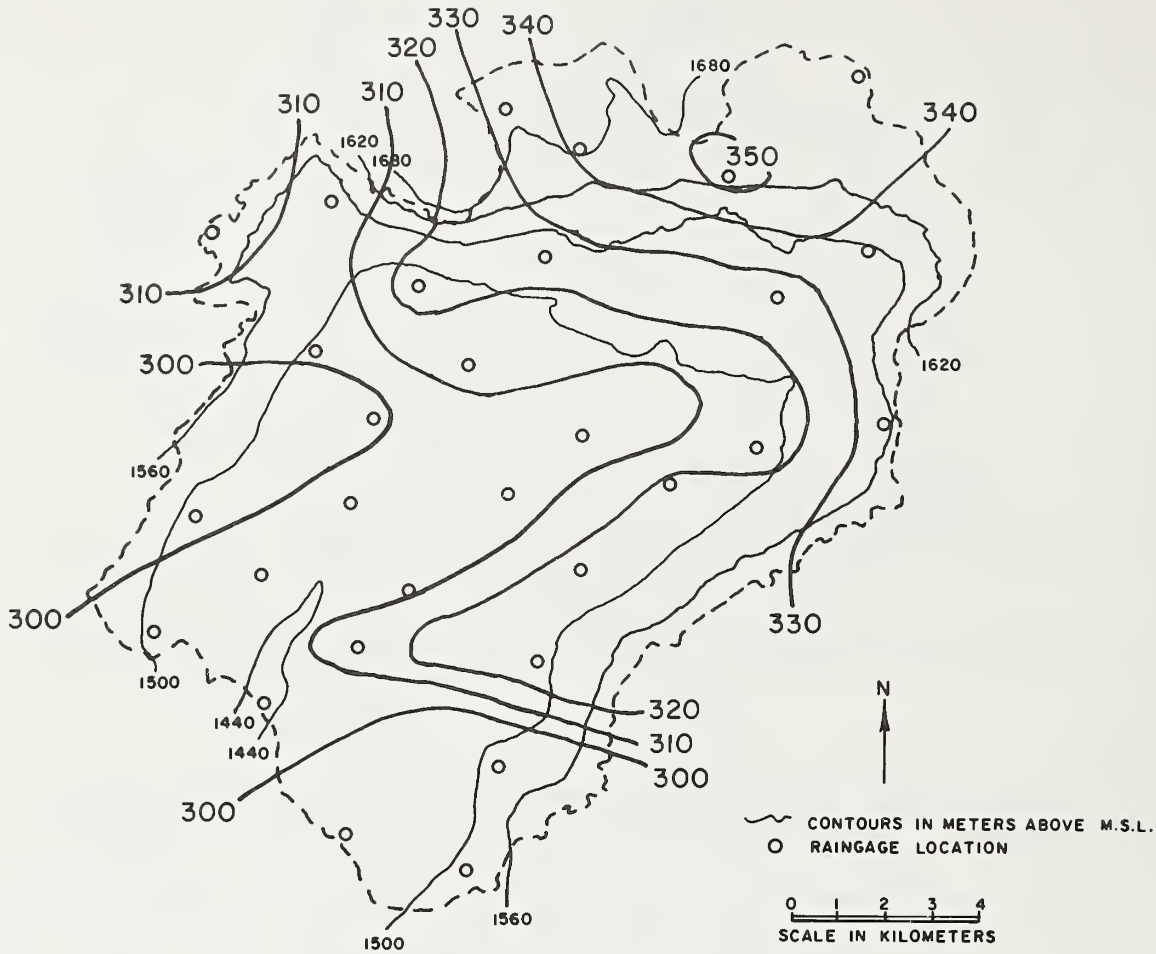

Figure 14.--Mean annual precipitation (mm) on Alamogordo Creek
Creek (1956-78).

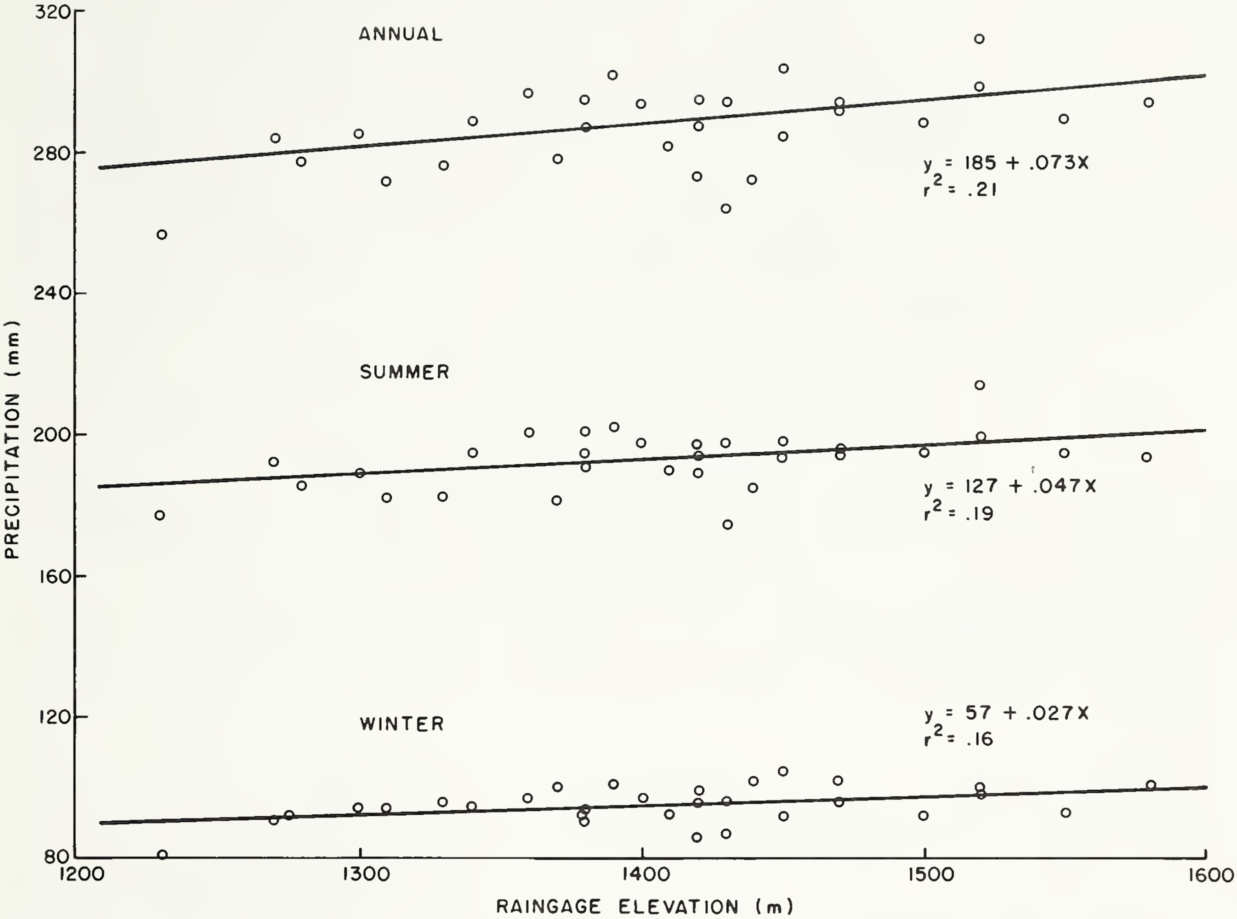

Figure 15.--Comparison of mean summer, winter, and annual point precipitation with elevation on Walnut Gulch.

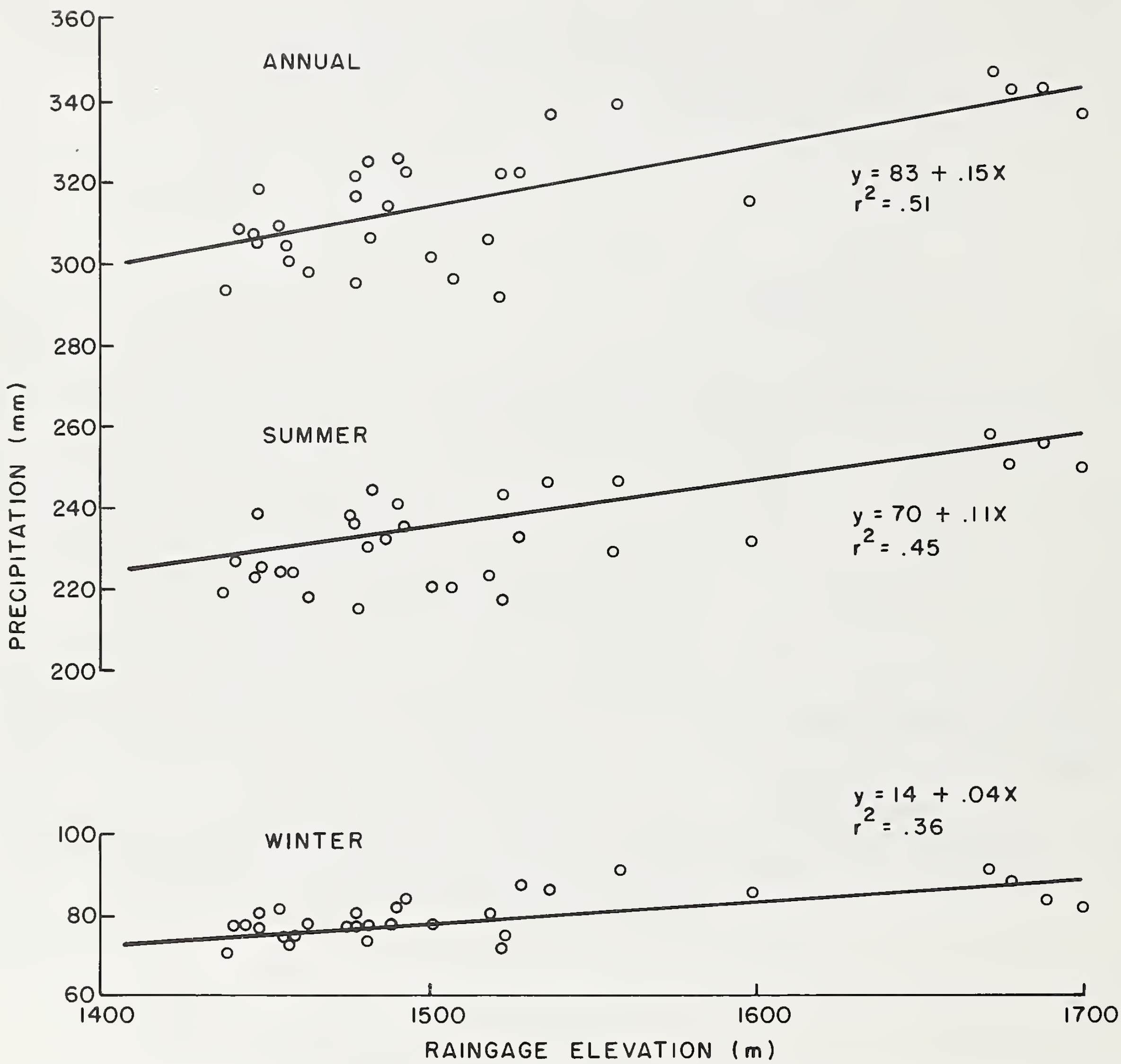

Figure 16.--Comparison of mean summer, winter, and annual point precipitation with elevation on Alamogordo Creek.

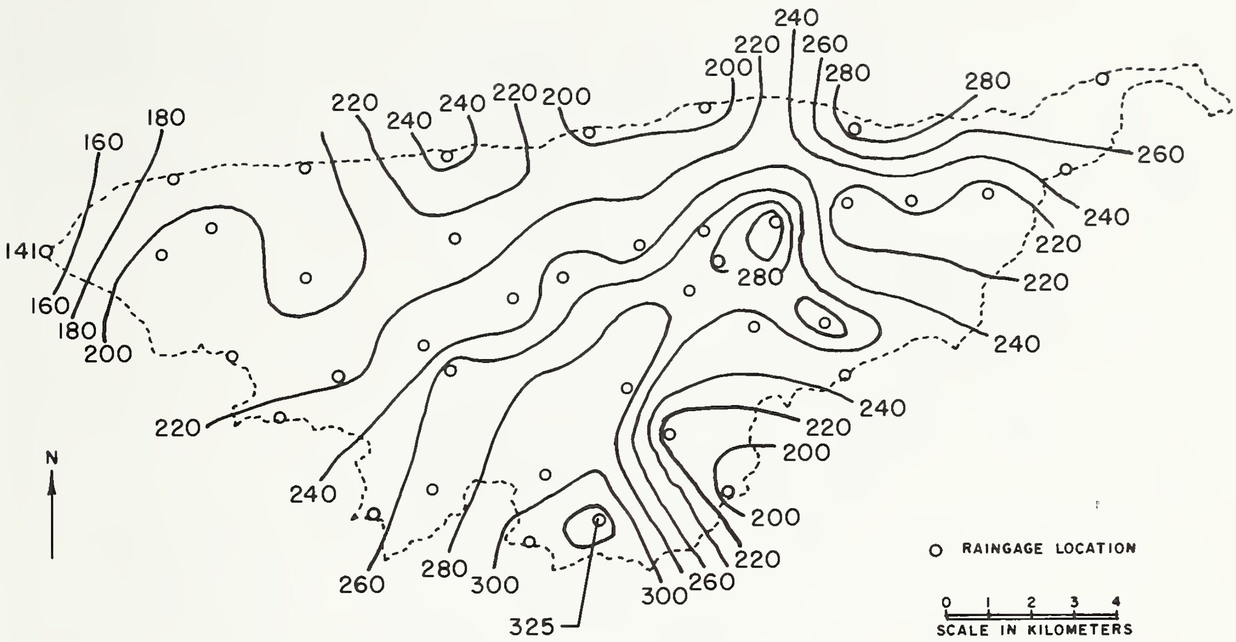

Figure 17.--Isohyetal map of 1967 summer rainfall (mm) on Walnut Gulch.

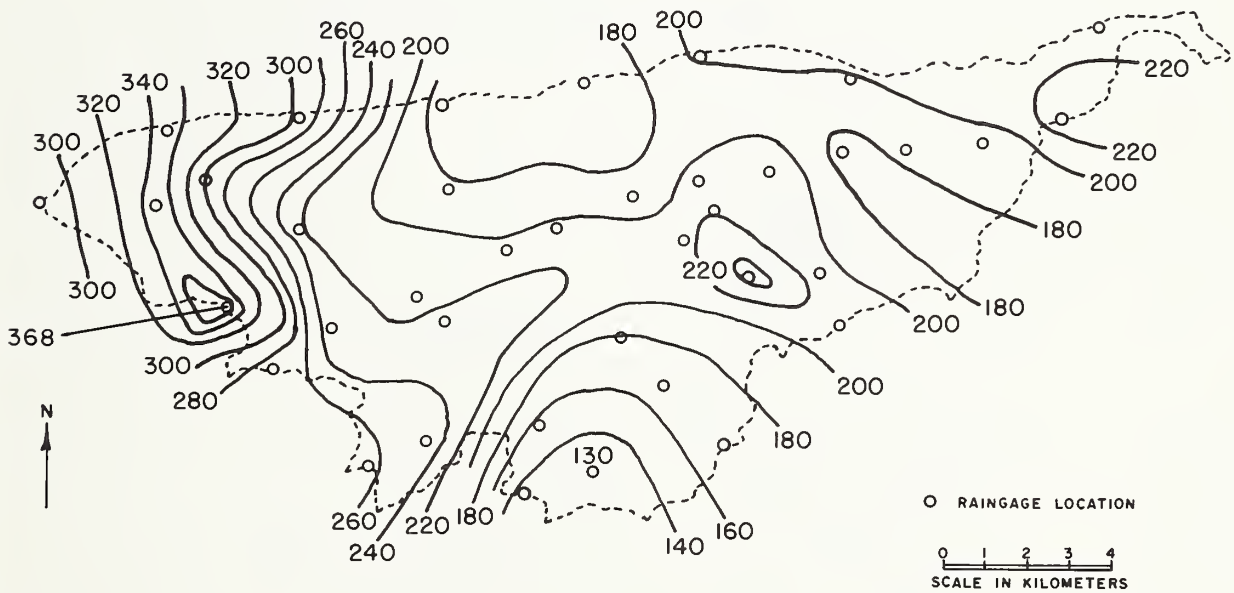

Figure 18.--Isohyetal map of 1969 summer rainfall (mm) on Walnut Gulch.

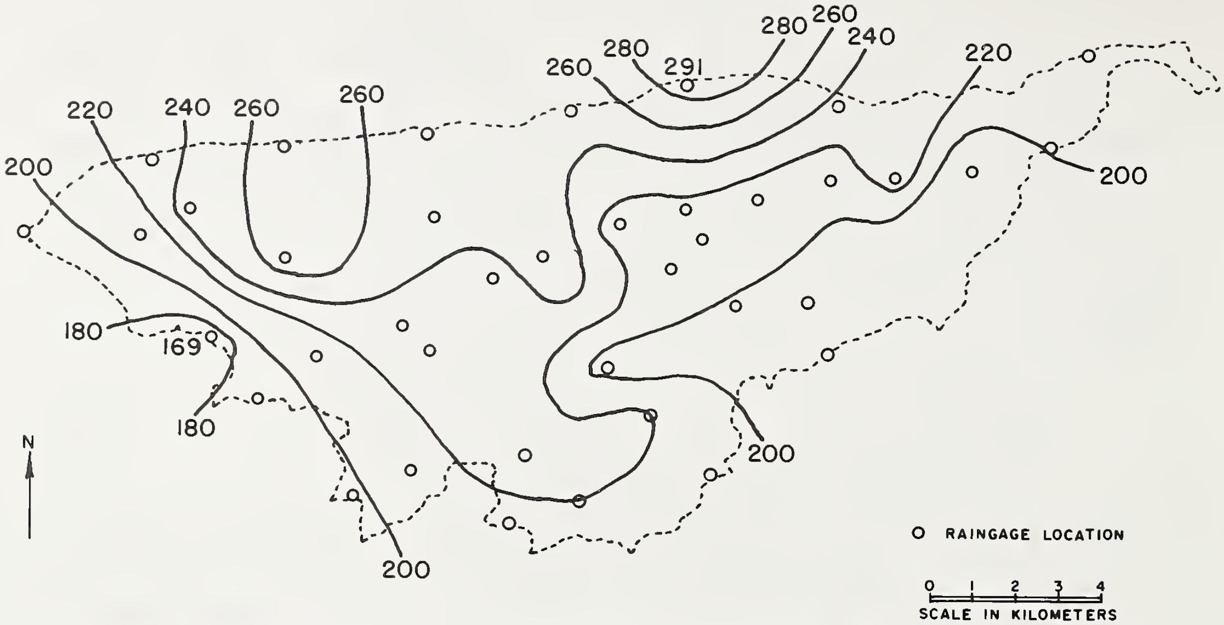

Figure 19.--Isohyetal map of 1977 summer rainfall (mm) on Walnut Gulch.

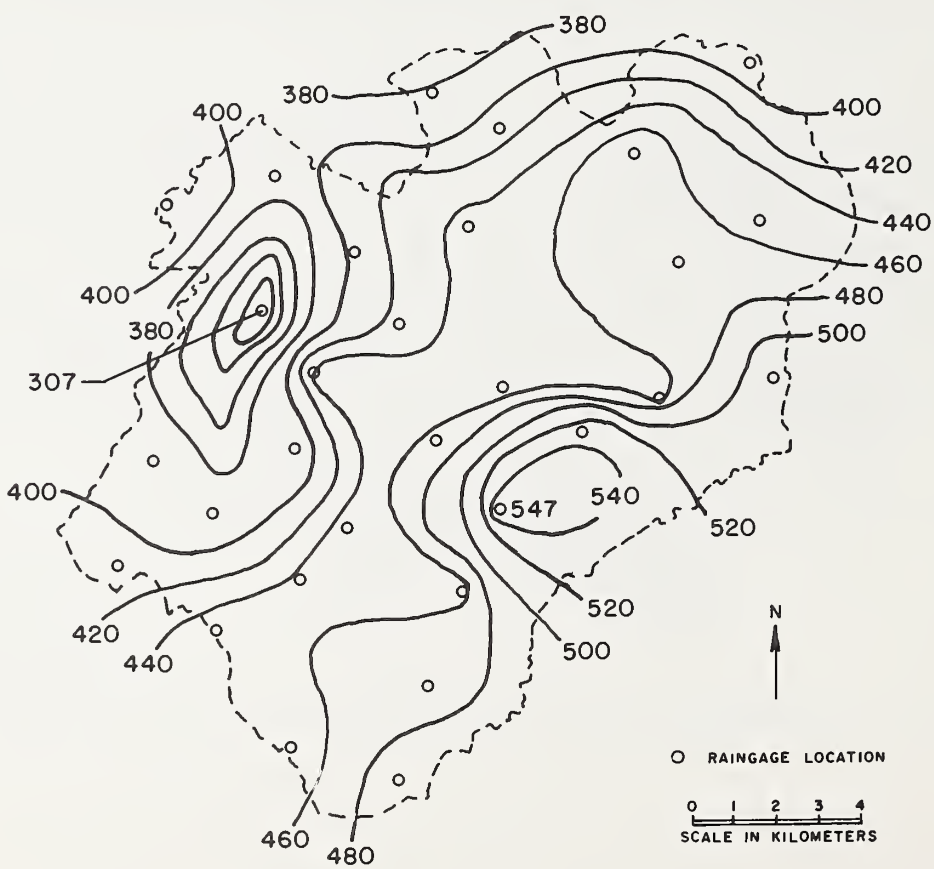

Figure 20.--Isohyetal map of 1972 summer rainfall (mm) for Alamogordo Creek.

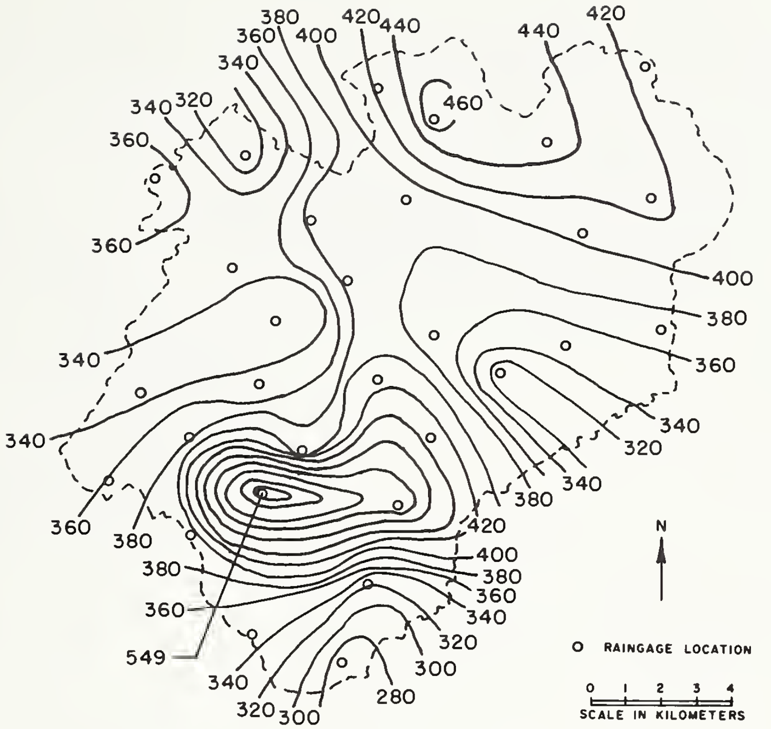

Figure 21.--Ishohyetal map of 1969 summer rainfall (mm) for Alamogordo Creek.

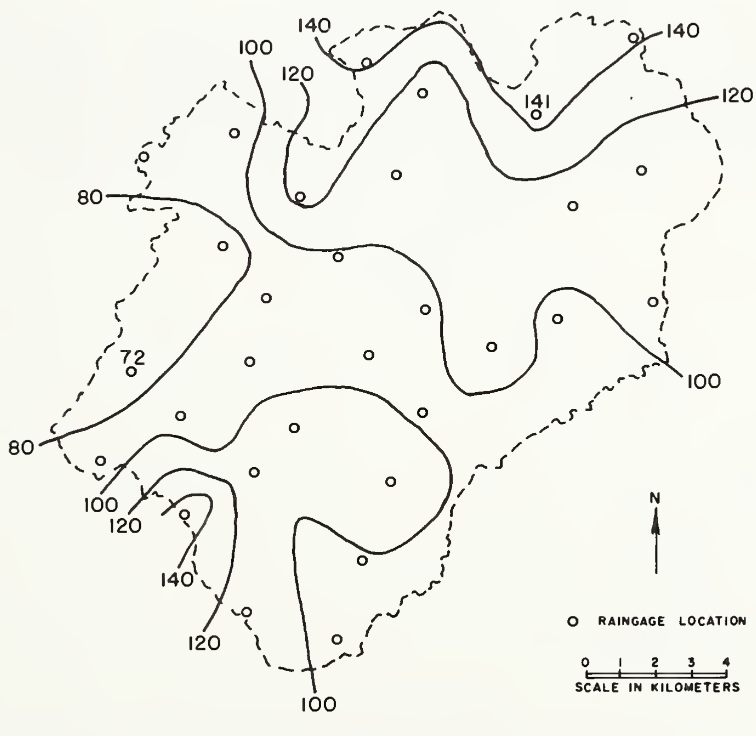

Figure 22.--Ishohyetal map of 1964 summer rainfall (mm) for Alamogordo Creek.

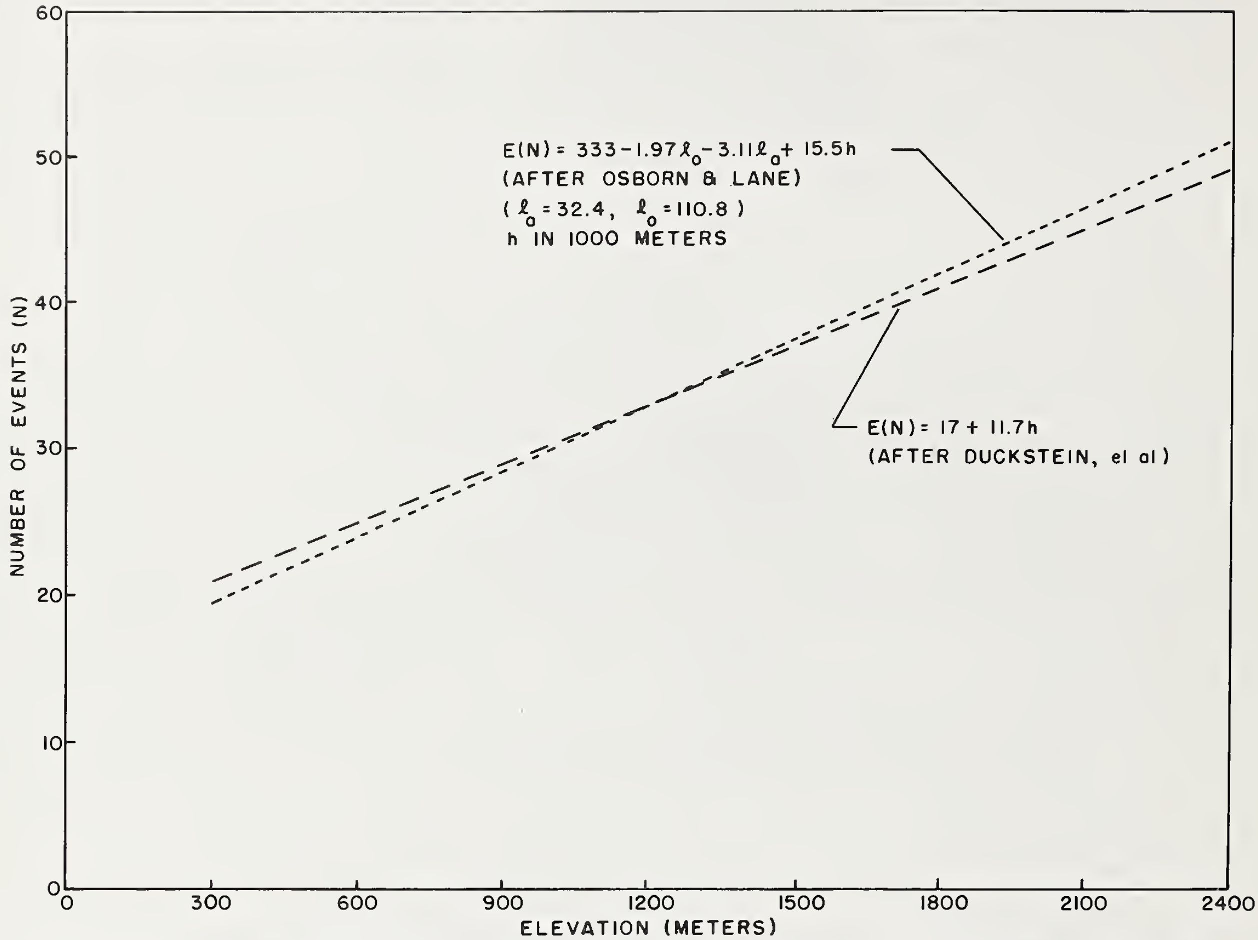

Figure 23.--Comparison of two equations for estimating the number of summer rains in the Santa Catalina Mountains of southern Arizona.

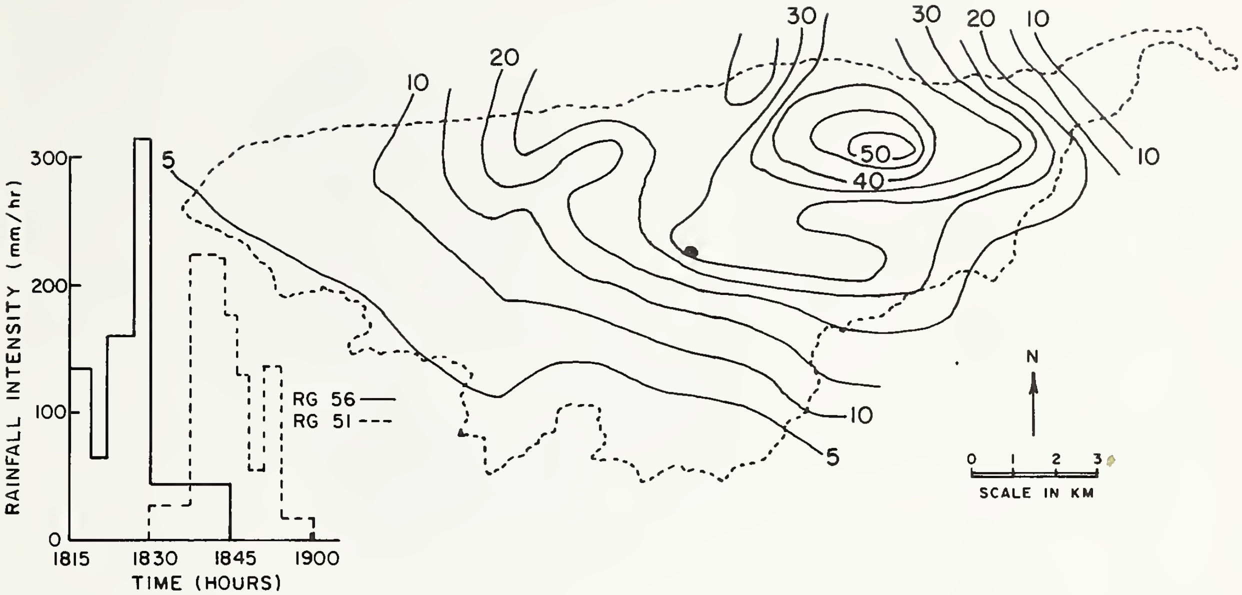

Figure 24.--Rainfall (mm) isohyetal map of hyetograph of storm on 22 July, 1964, on Walnut Gulch.

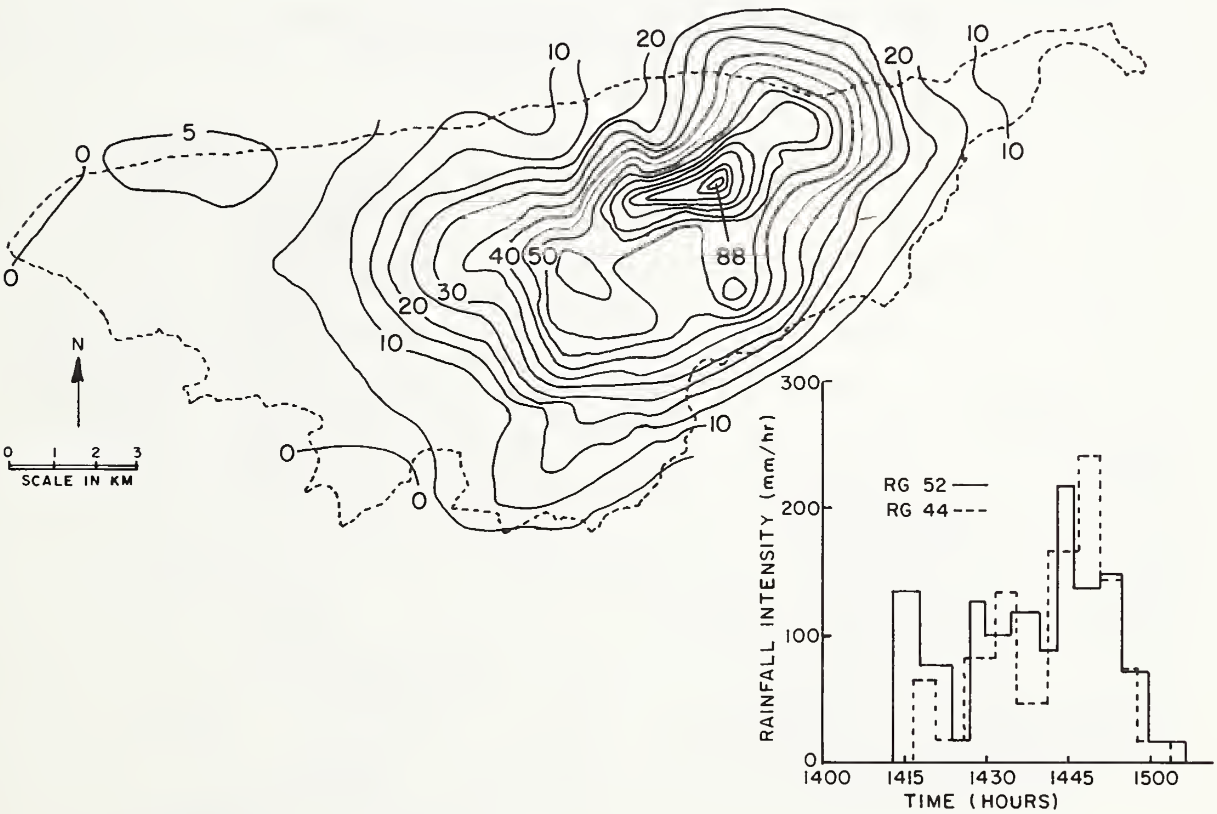

Figure 25.--Rainfall (mm) isohyetal map and hyetograph of storm on 10 September, 1967, on Walnut Gulch.

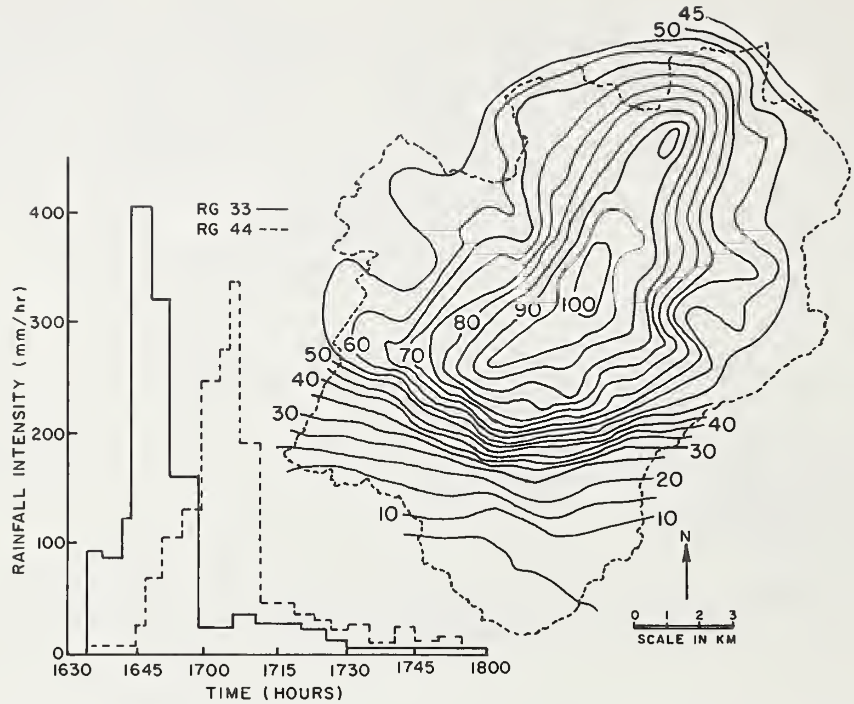

Figure 26.--Rainfall (mm) isohyetal map and hyetograph of storm on 5 June, 1960, on Alamogordo.

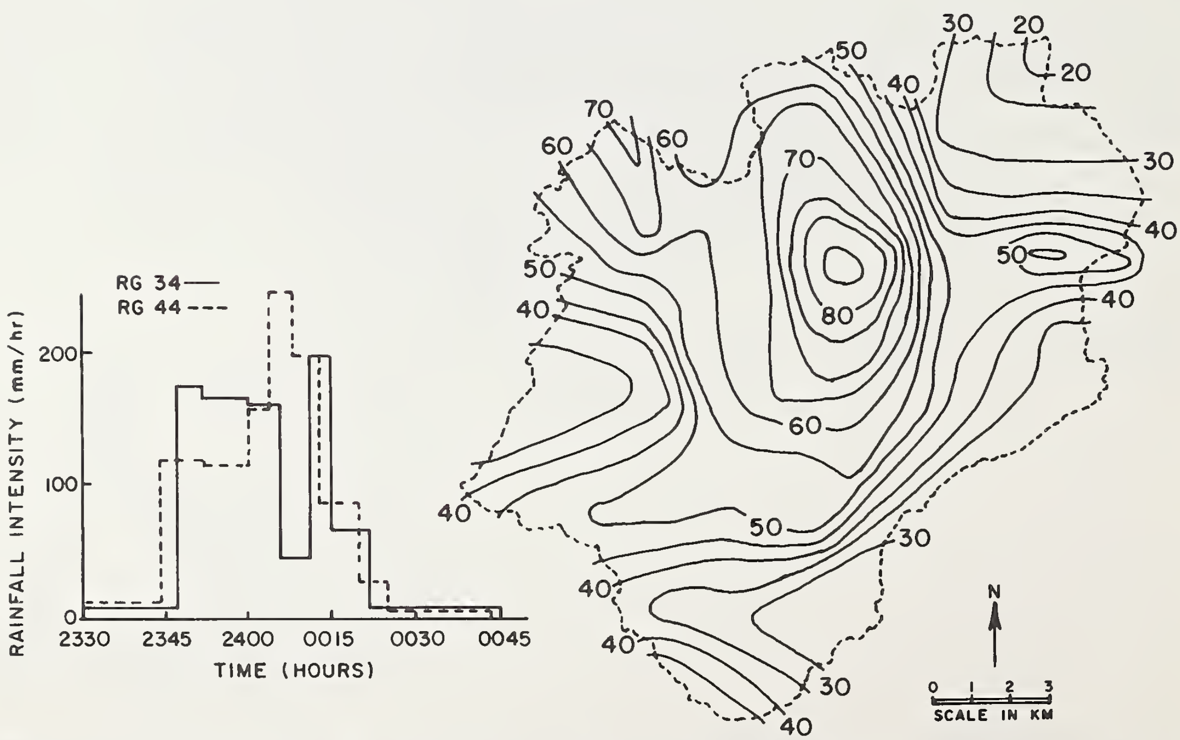

Figure 27.--Rainfall (mm) isohyetal map and hyetograph of storm on 16/17 June, 1966, on Alamogordo Creek.

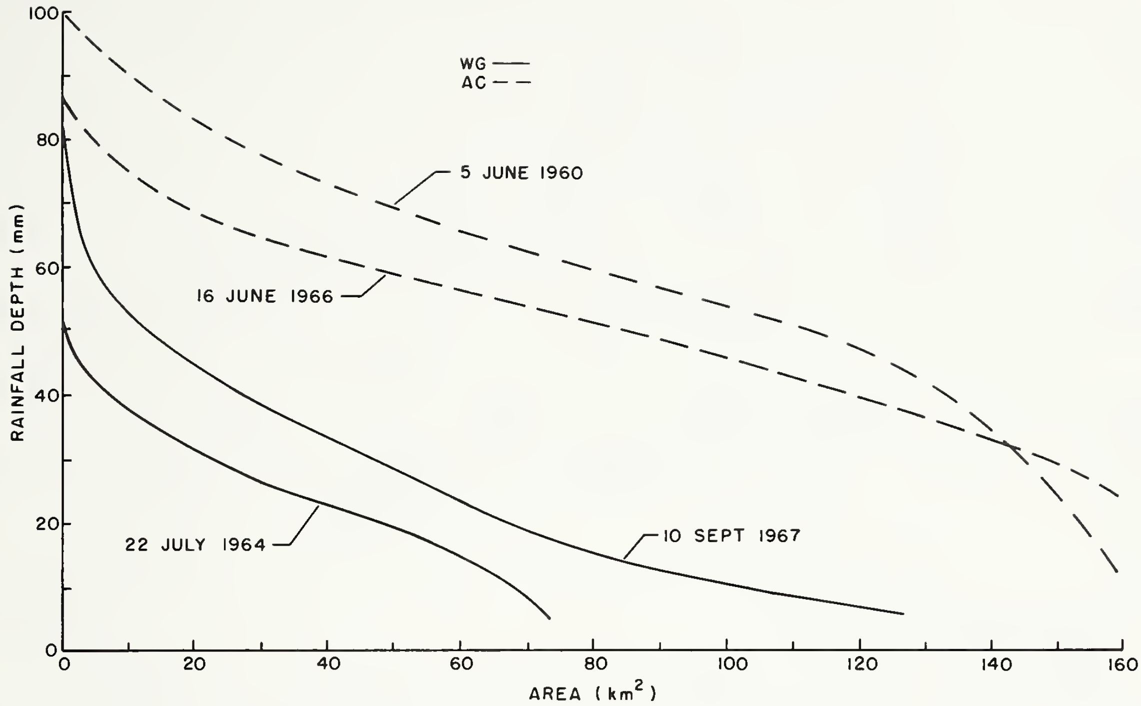

Figure 28.--Depth-area rainfall curves for selected events on Walnut Gulch and Alamogordo Creek.

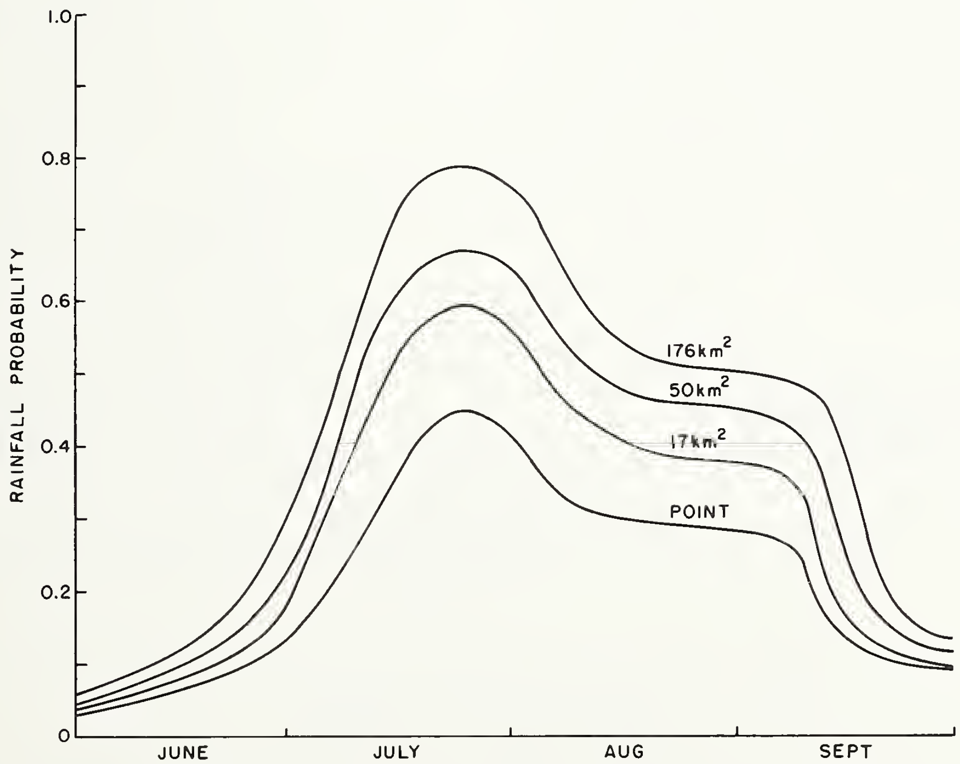

Figure 29.--Probability of measureable rainfall (0.25 mm) on Walnut Gulch.

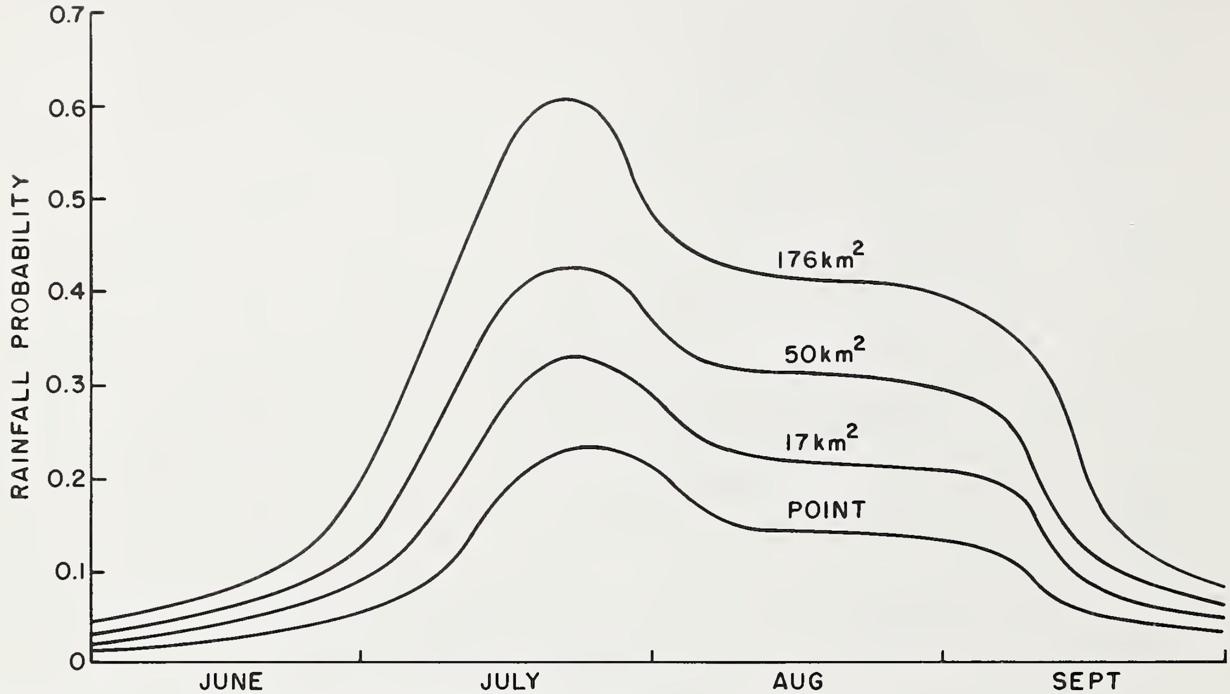

Figure 30.--Probability of significant summer rainfall ($\geq$5 mm) on Walnut Gulch.

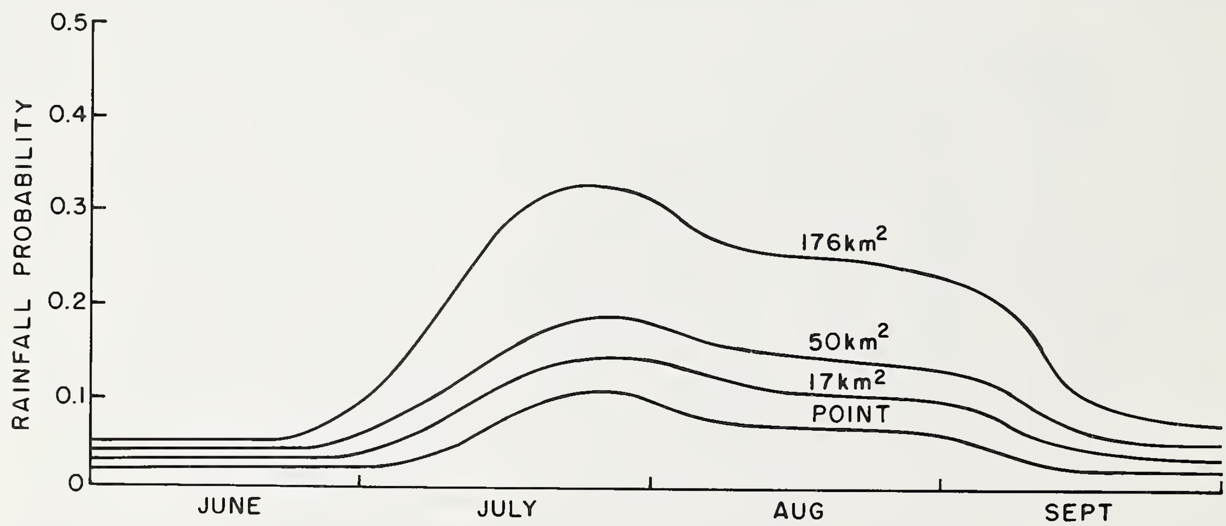

Figure 31.--Probability of runoff-producing summer rainfall ($\geq$15 mm) on Walnut Gulch.

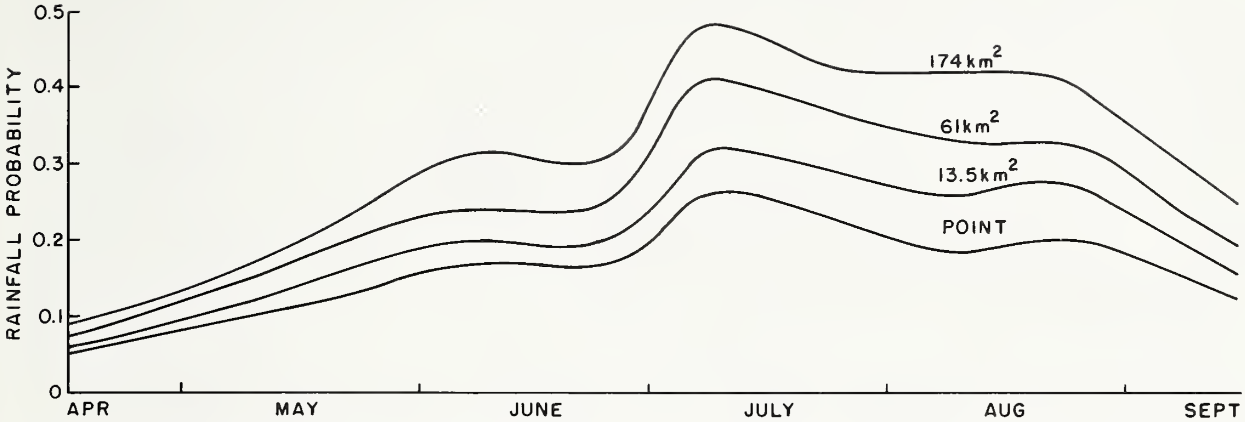

Figure 32.--Probability of measureable rainfall ($\geq$0.25 mm) on Alamogordo Creek.

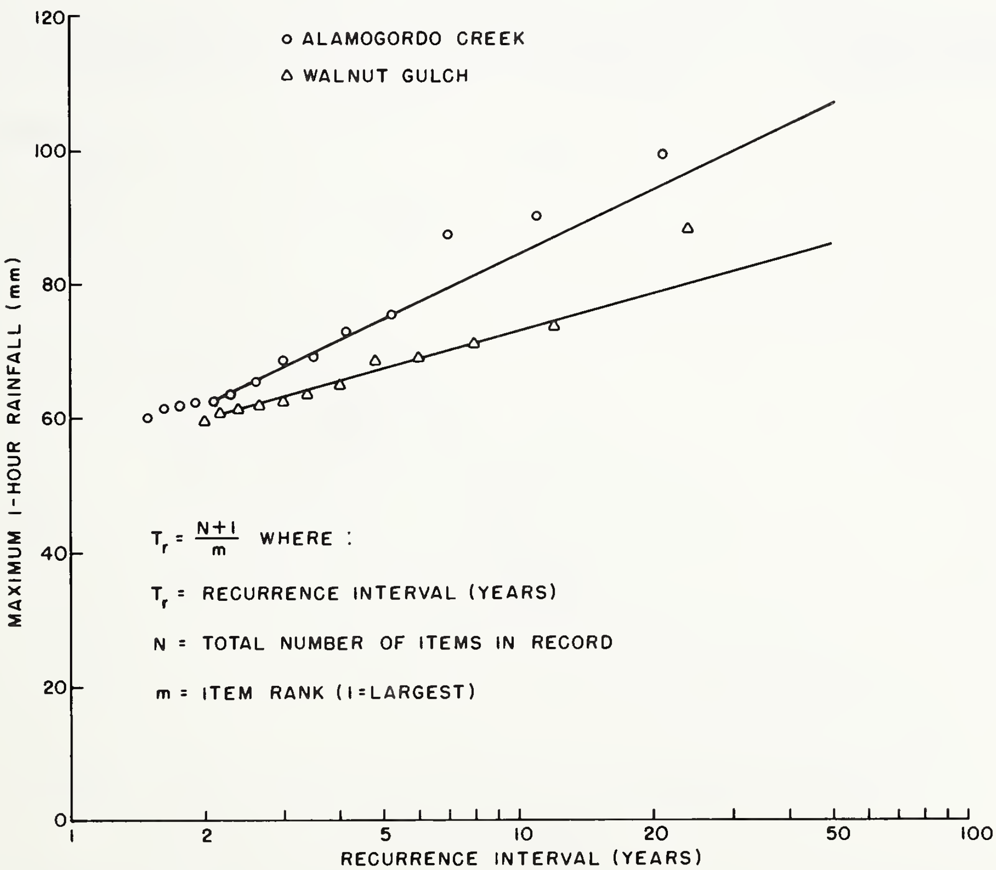

Figure 33.--Recurrence intervals for maximum 1-hr rains on Walnut Gulch and Alamogordo Creek based on 25 and 23 years of data, respectively.

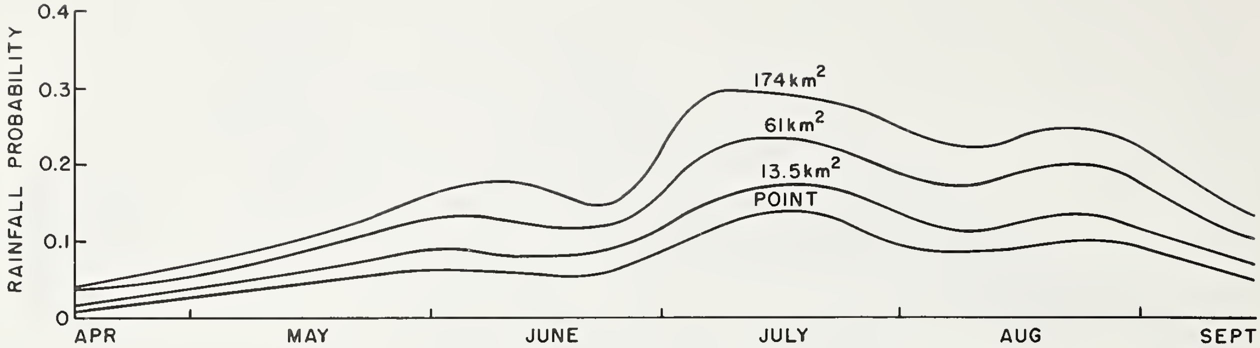

Figure 34.--Probability of significant rainfall (≥5 mm) on Alamogordo Creek.

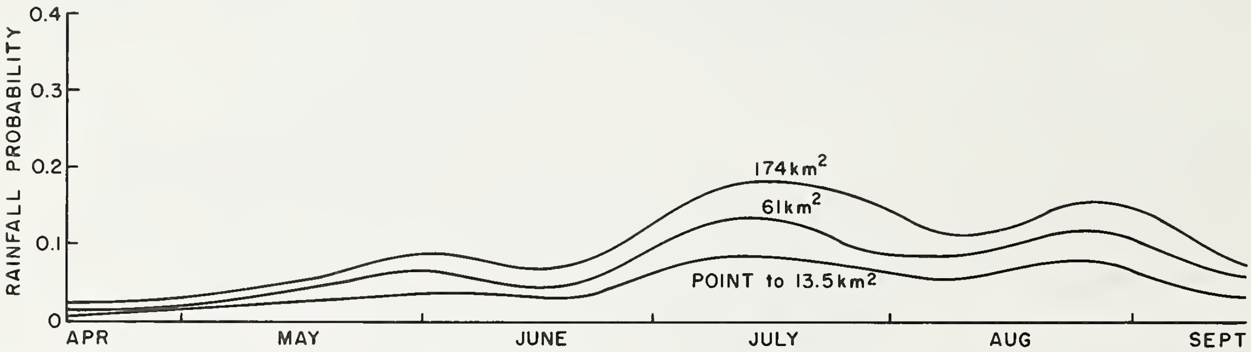

Figure 35.--Probability of runoff-producing rainfall (≥15 mm) on Alamogordo Creek.

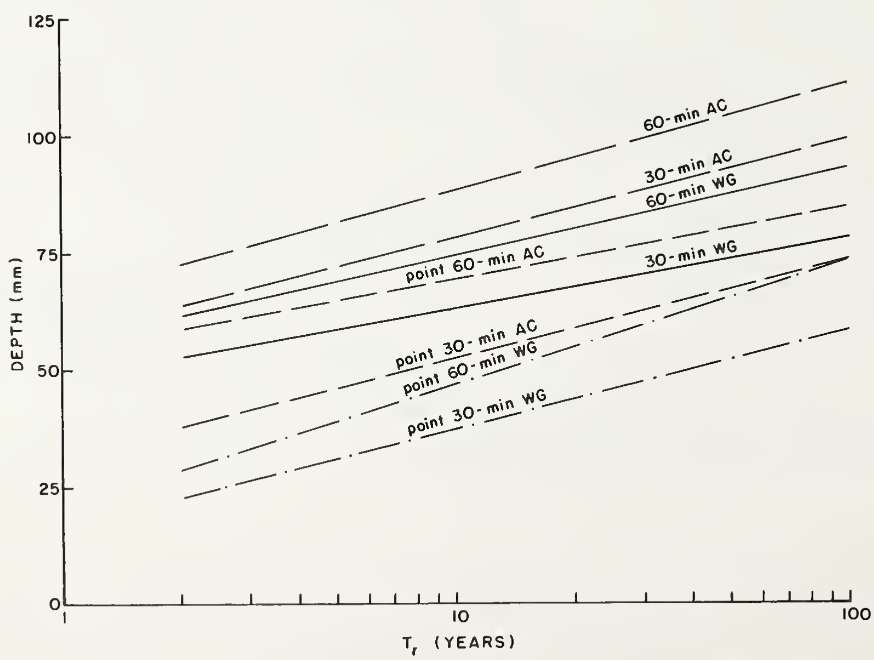

Figure 36.--Expected point and watershed 30- and 60-min rainfall depths for Walnut Gulch (WG) and Alamogordo Creek (AC).

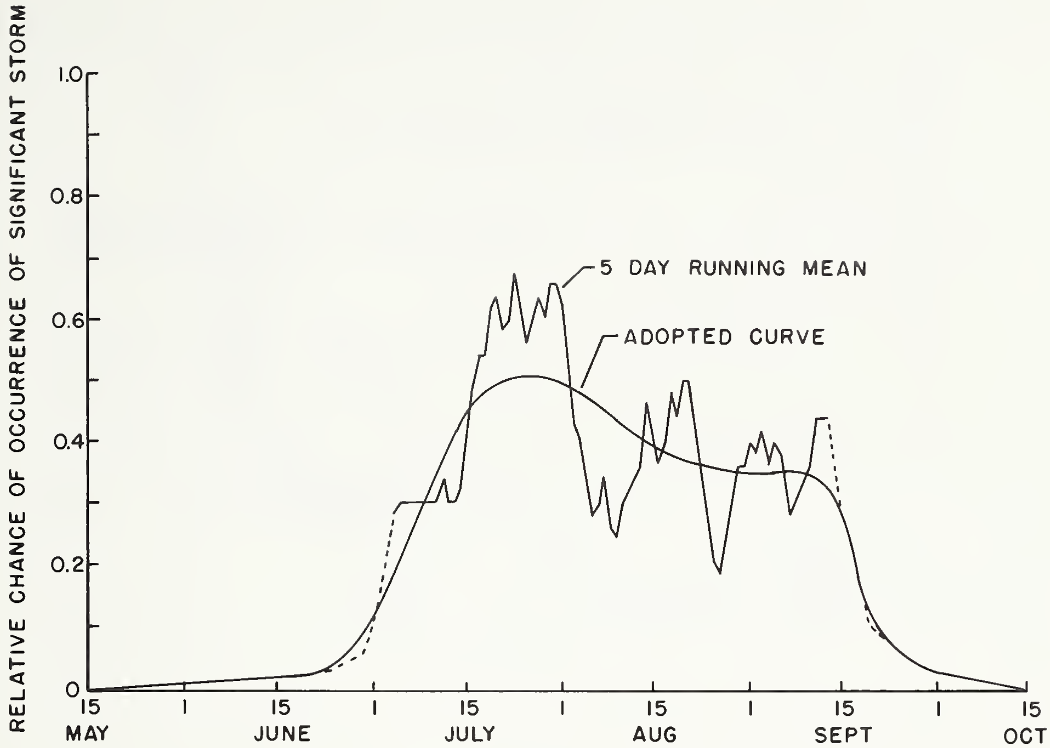

Figure 37.--Empirically derived curve for the probability of significant daily rainfall on Walnut Gulch.

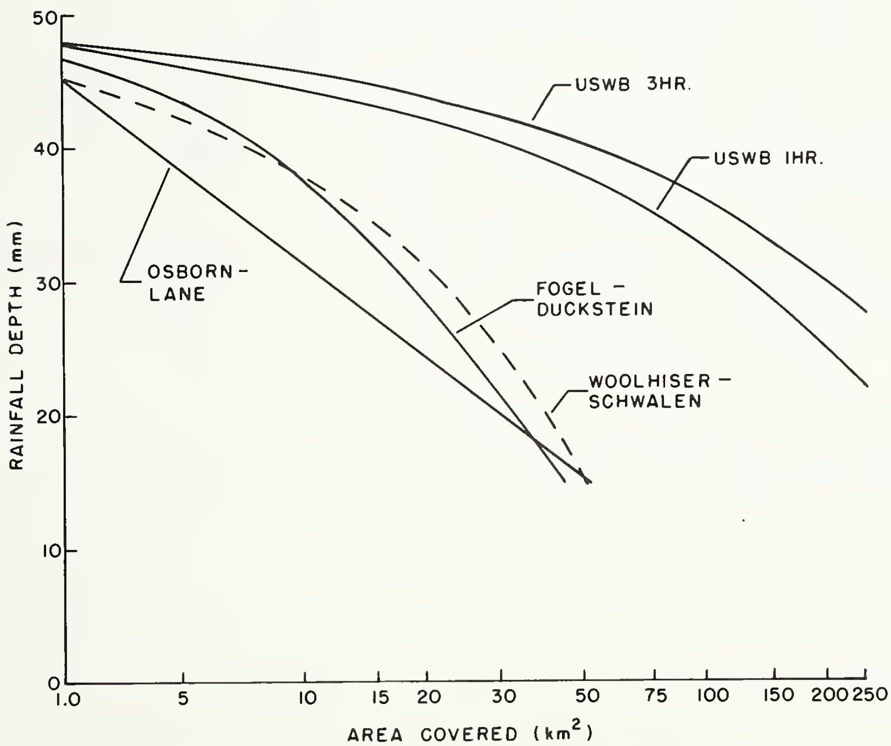

Figure 38.--Comparison of depth-area relationships for thunderstorms in southern Arizona for a 50-mm center depth.

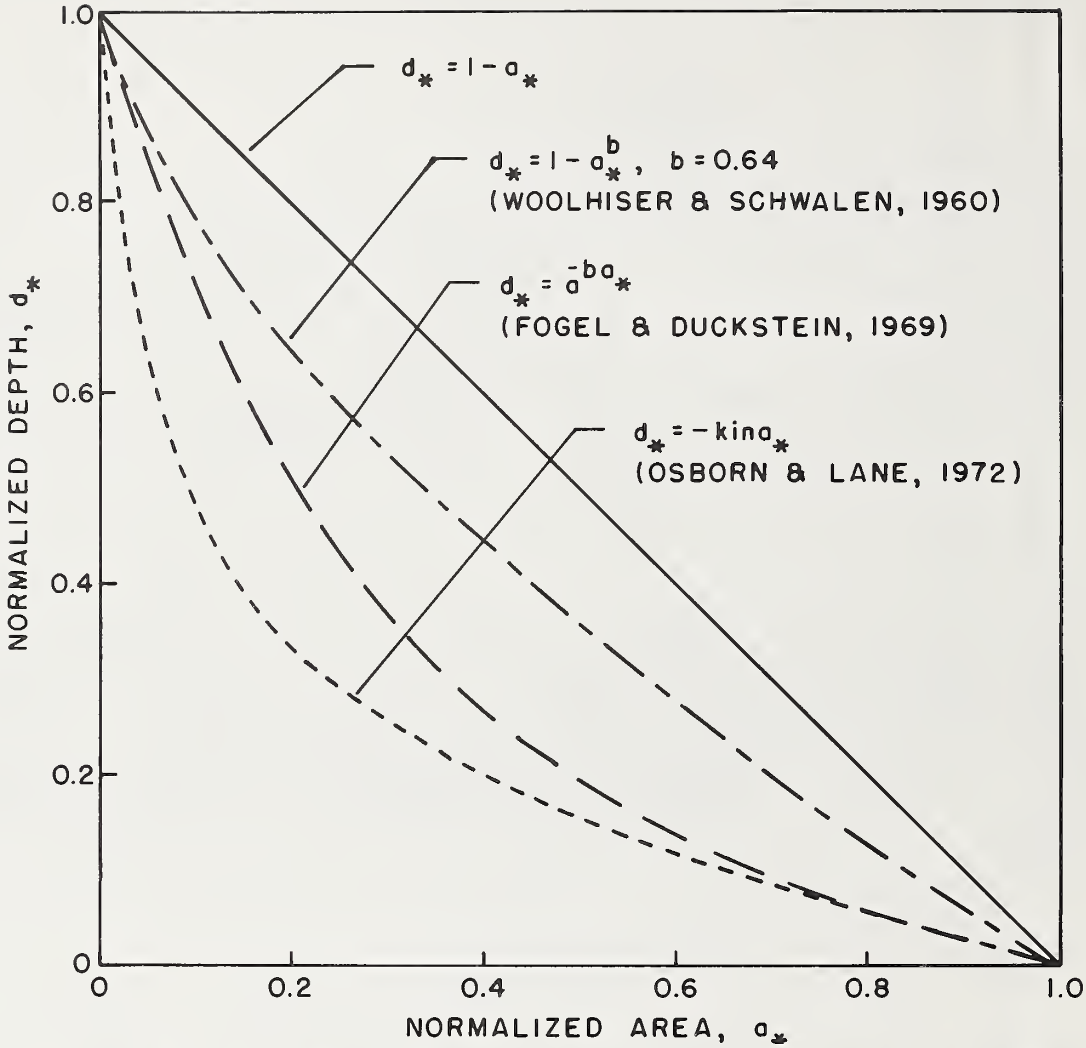

Figure 39.--Normalized depth-area relations for selected airmass thunderstorm rainfall models (after Smith (51)).

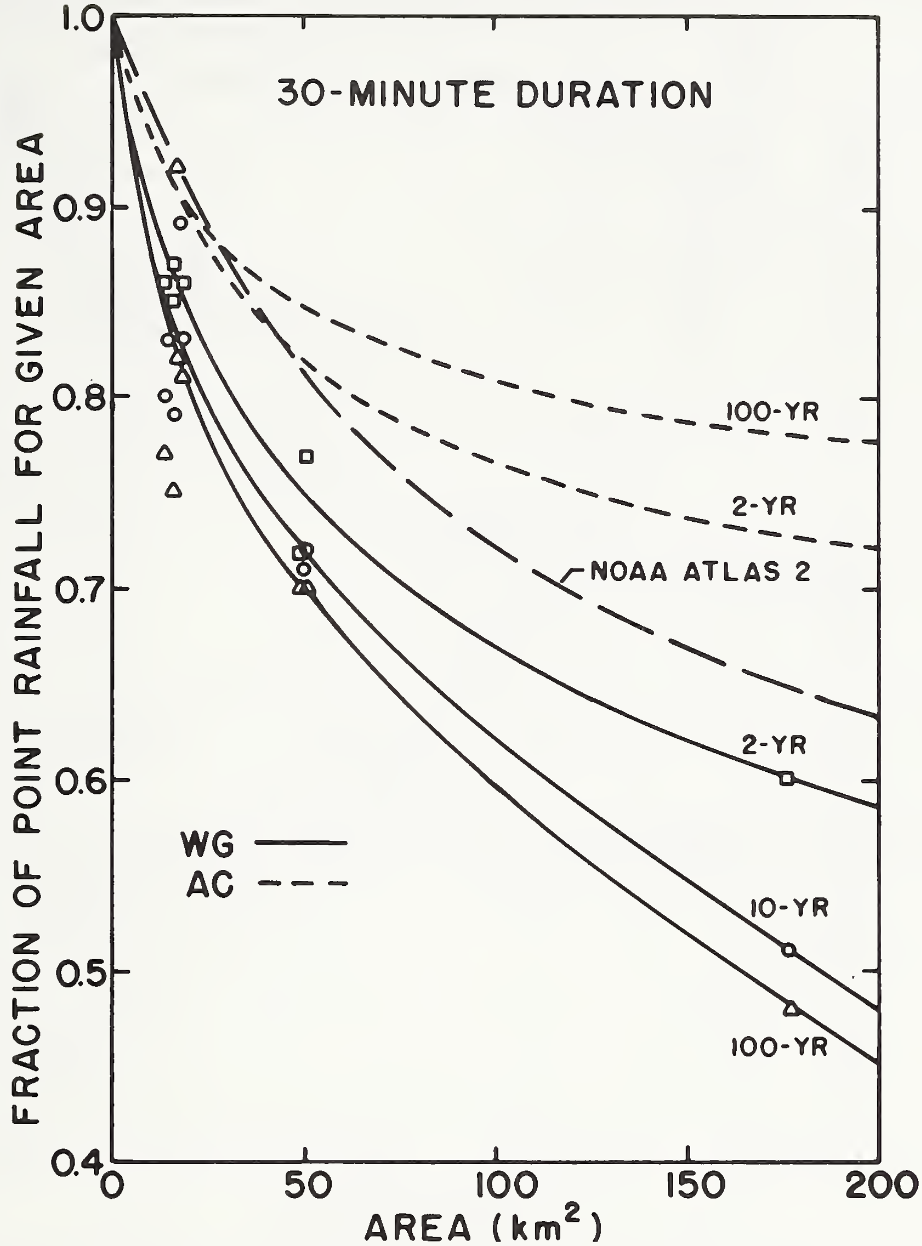

Figure 40.--Point-to-area conversion ratios for 30-min duration rainfall for selected frequencies on Walnut Gulch and Alamogordo Creek.

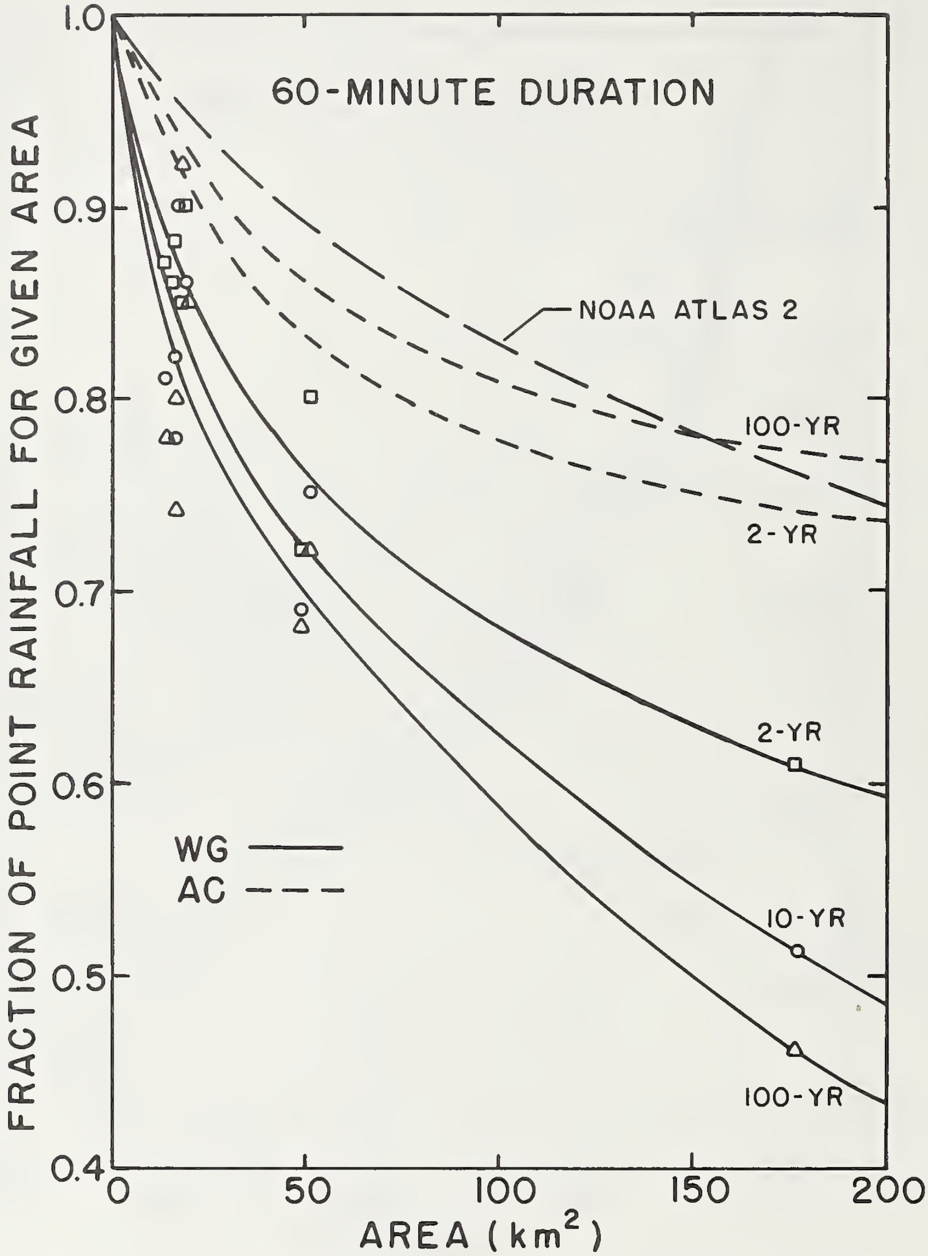

Figure 41.--Point-to-area conversion ratios for 60-min duration rainfall for selected frequencies on Walnut Gulch and Alamogordo Creek.

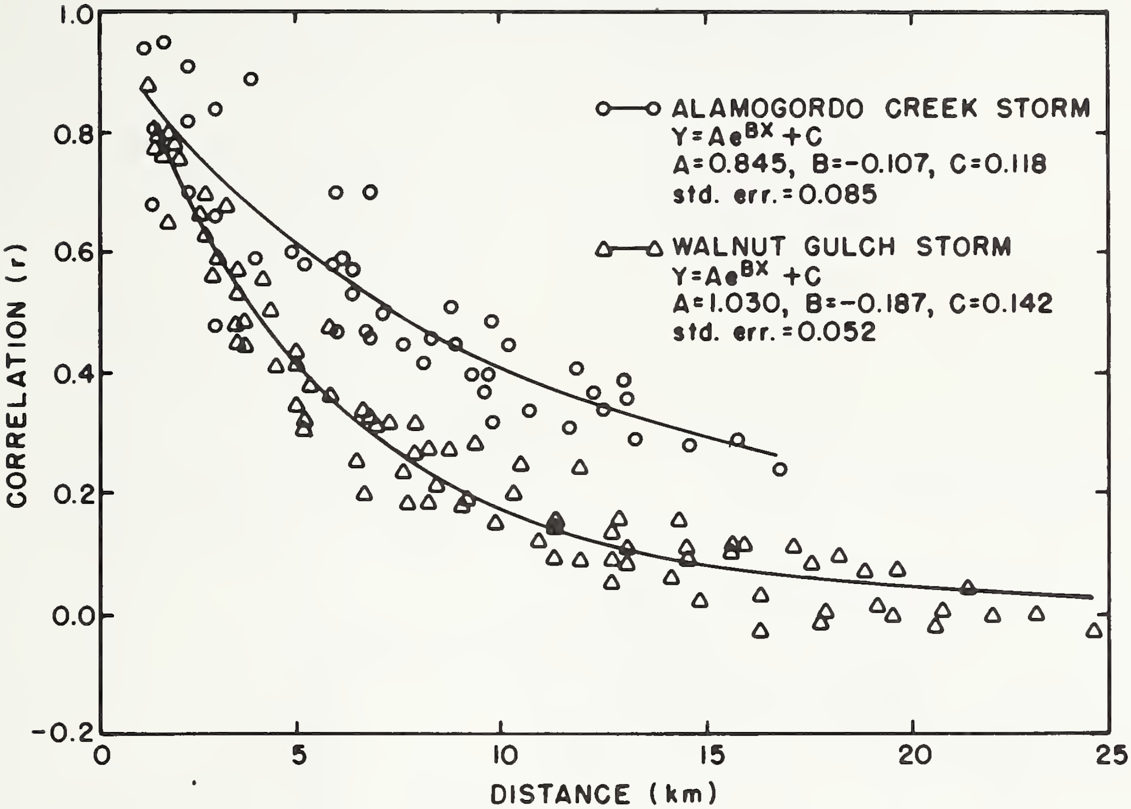

Figure 42.--Correlation coefficients for storm rainfall for preselected pairs of raingages on Walnut Gulch and Alamogordo Creek.

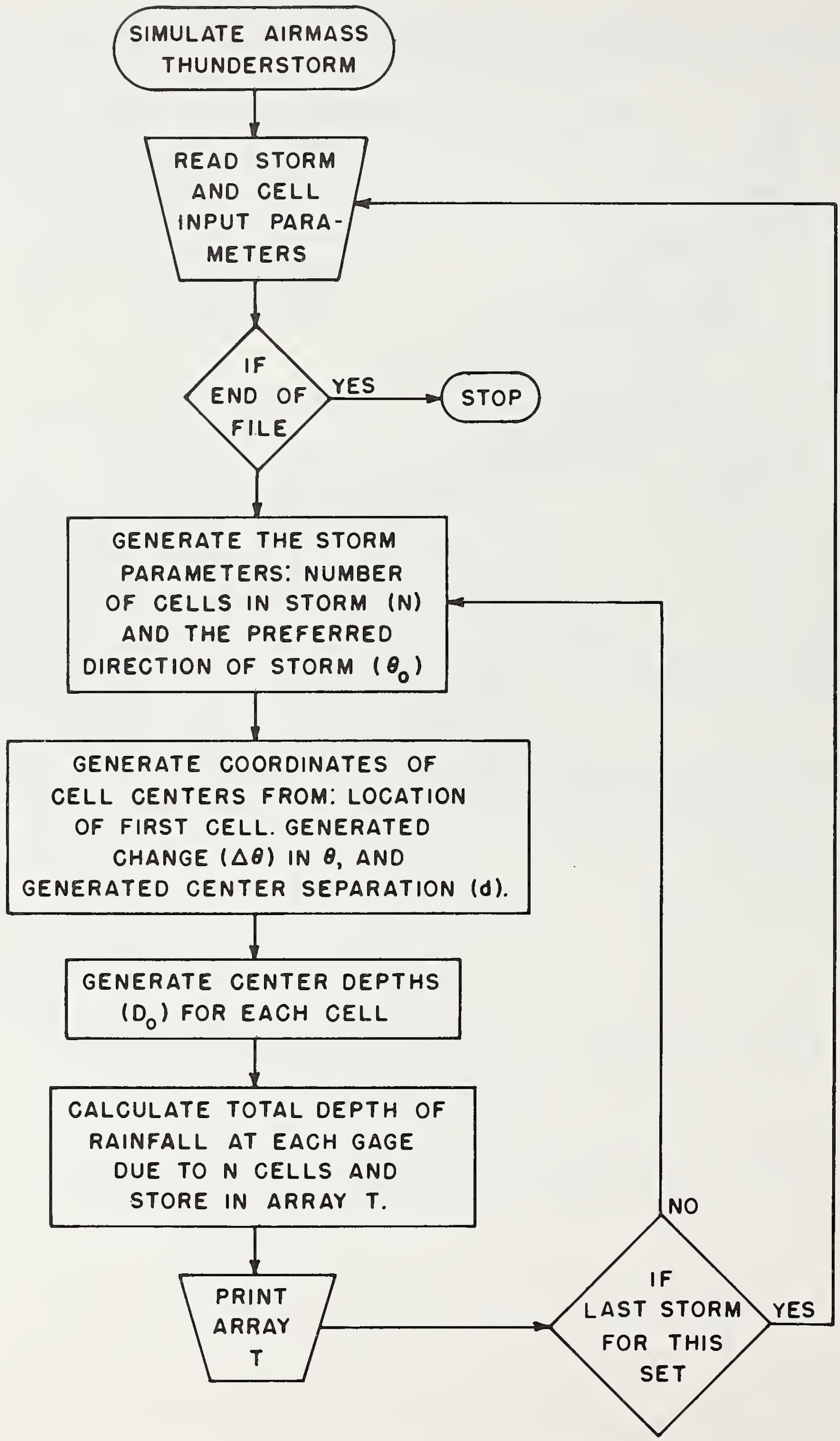

Figure 43.--Flow chart for simulation of individual airmass thunderstorm rains.

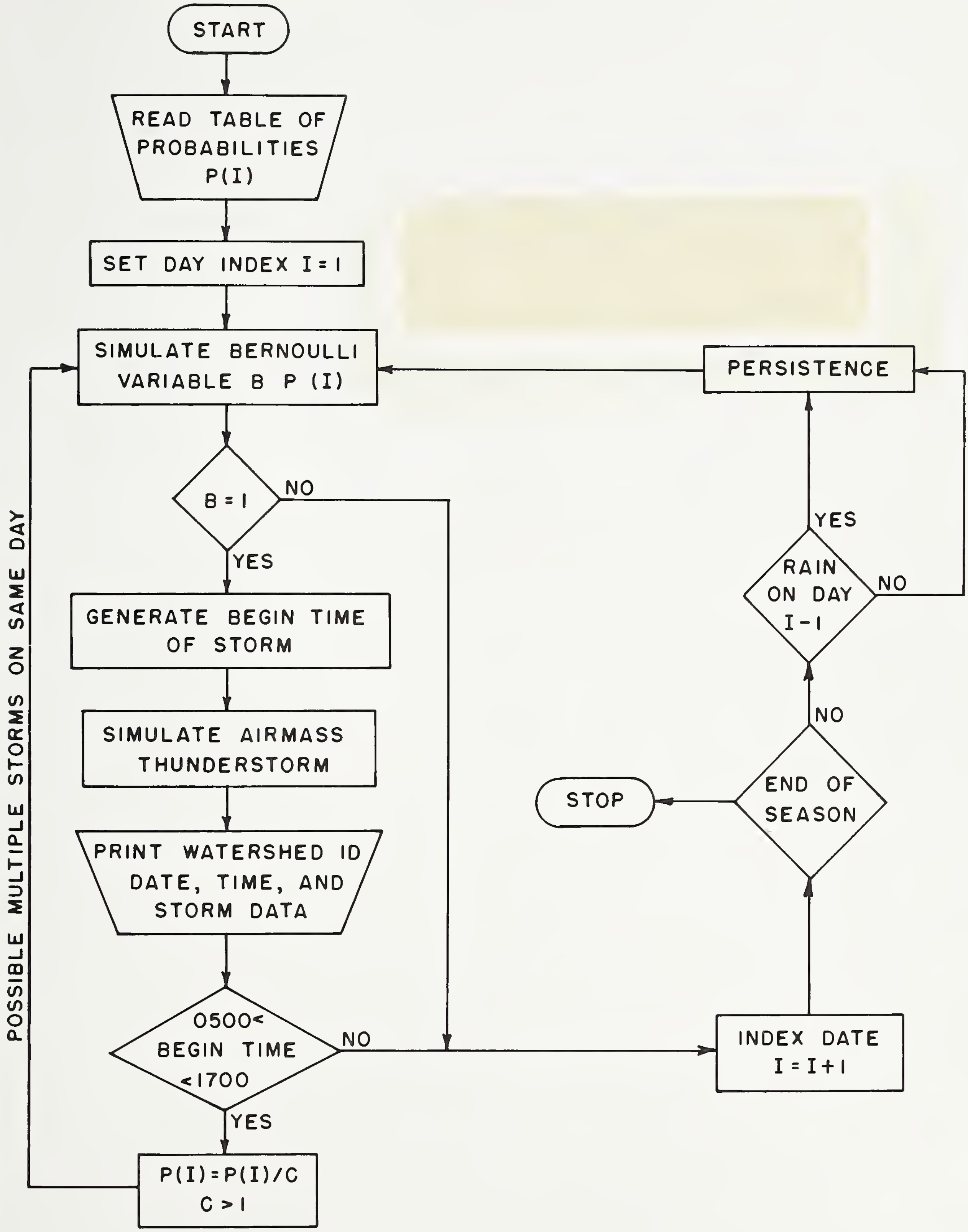

Figure 44.--Flow chart for generating seasonal synthetic rainfall data.

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